On the intensity of the extragalactic X-ray background

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\textbf{ABSTRACT}
Measurements of the intensity of the cosmic X-ray background (XRB) carried out over small solid angles are subject to spatial variations due to the discrete nature of the XRB. This cosmic variance can account for the dispersion of XRB intensity values found within the ASCA, BeppoSAX and ROSAT missions separately. However, there are differences among the values obtained in the different missions which are not due to spatial fluctuations but, more likely, to systematic cross-calibration errors. Prompted by recent work which shows that ROSAT PSPC has calibration differences with all the other missions, we compute a bayesian estimate for the XRB intensity at 1 keV of $10^{−3} ± 0.6$ keV cm$^{-2}$ s$^{-1}$ sr$^{-1}$ keV$^{-1}$ (90 per cent confidence errors) using the ASCA and BeppoSAX data points. However, this value is still significantly larger than the HEAO − 1 intensity measured over many thousands of square degrees (8 keV cm$^{-2}$ s$^{-1}$ sr$^{-1}$ keV$^{-1}$).

\textbf{Key words:} Cosmology: diffuse radiation – X-rays: general.

\section{1 INTRODUCTION}

Most of the X-ray background (XRB) above photon energies of a few keV is known to be extragalactic in origin (see, e.g. reviews by Boldt 1987 and Fabian & Barcons 1992). Its spectrum was well measured by the HEAO − 1 A2 experiment in the 3-50 keV energy range (Marshall et al 1980), where it fits a thermal bremsstrahlung model with a temperature $kT ≈ 40$ keV. An overall fit to the XRB spectrum from 3 keV to 10 MeV was presented by Gruber (1992) based on data from the A2 and A4 experiments on board HEAO − 1, which showed an extrapolated intensity at 1 keV of $≈ 8$ keV cm$^{-2}$ s$^{-1}$ sr$^{-1}$ keV$^{-1}$.

More recently, measurements of the XRB spectrum and intensity at photon energies < 10 keV have been obtained with the use of imaging instruments. Using ASCA data, Gendreau et al (1995) confirmed that the thermal bremsstrahlung shape (which at photon energies below $~ 20$ keV can be approximated by a power law with energy spectral index $α ≈ 0.37$) provides a good fit to the XRB spectrum down to about 1 keV, Vecchi et al (1999) used the LECS and MECS instruments on board BeppoSAX in the 1-8 keV band to confirm that the XRB spectrum is consistent with a power law with $α ≈ 0.4$.

ROSAT PSPC observations have also provided data on the spectrum of the extragalactic XRB. Hasinger (1992) found a very steep spectrum for the XRB below 2 keV ($α ≈ 1$). However, shadowing experiments with ROSAT have provided the more stringent upper limits to the slope of the extragalactic XRB at soft X-ray energies ($α < 0.7$, Barber & Warwick 1994). The relative steepness of the ROSAT spectra with respect to many other instruments has been studied in detail by Iwasawa, Fabian & Nandra (1999). The fact that the spectral shape of the same sources is usually consistent in observations of many instruments with the exception of ROSAT (which usually finds steeper spectra) is highly suggestive of a calibration mismatch which will certainly affect the XRB spectrum as well.

The normalisation of the extragalactic XRB (that we parametrise as the XRB intensity $I_{XRB}$ at 1 keV in units of keV cm$^{-2}$ s$^{-1}$ sr$^{-1}$ keV$^{-1}$) remains uncertain. The Marshall et al (1980) measurement is the most robust result as it was performed over a very large solid angle ($~ 10^4$ deg$^2$) with instrumentation especially designed to subtract efficiently and accurately the particle background. The XRB intensity measured by the imaging instruments on board ASCA, BeppoSAX and ROSAT invariably yield higher values which are often statistically discrepant among them.

In this paper we point out that the discrete nature of the XRB introduces a cosmic variance in its intensity which is large for observations carried out over small solid angles. This cosmic variance is just the confusion noise caused by unresolved or non removed sources in the images (Scheuer 1974, Barcons 1992). We find variations of the order of 10 per cent for solid angles under 1 deg$^2$ and therefore cosmic variance often dominates over the statistical uncertainties quoted in the various estimates of the XRB intensity. Once this is included, we combine individual measurements of the
XRB to compute bayesian estimates of the overall XRB intensity. We find that measurements carried out within the same mission are brought to consistency by cosmic variance, but that systematic differences between different missions remain.

Table 1 lists the XRB intensity measurements that we have included. Measurements of the XRB intensity at 1 keV carried out with imaging instruments.Ω

| Instrument   | Name   | Field | $\Omega_i$ (deg$^2$) | $S_i$ (keV cm$^{-2}$ s$^{-1}$ sr$^{-1}$ keV$^{-1}$) | $\sigma_i$ | $\Sigma_i$ | Ref |
|--------------|--------|-------|----------------------|-----------------------------------------------|-----------|-----------|-----|
| ROSAT PSPC   | QSF3   | 0.223 | 11.4                | 0.34                                           | 1.00      | Chen et al (1996) |
| ASCA SIS     | QSF3   | 0.134 | 10.0                | 0.37                                           | 0.76      | Chen et al (1996) |
| ROSAT PSPC   | GSGP4  | 0.283 | 11.8                | 0.40                                           | 0.49      | Georgantopoulos et al (1996) |
| ROSAT PSPC   | SG2P   | 0.283 | 12.0                | 0.61                                           | 0.53      | Georgantopoulos et al (1996) |
| ROSAT PSPC   | SG3P   | 0.283 | 12.0                | 0.68                                           | 0.52      | Georgantopoulos et al (1996) |
| ROSAT PSPC   | QSF1   | 0.283 | 9.9                 | 0.65                                           | 0.49      | Georgantopoulos et al (1996) |
| ASCA GIS     | Lockman| 0.165 | 10.9                | 0.61                                           | 0.13      | Miyaji et al (1998) |
| ASCA GIS     | Lynx   | 0.144 | 9.3                 | 0.61                                           | 0.13      | Miyaji et al (1998) |
| ROSAT PSPC   | Lockman| 0.165 | 10.0                | 0.30                                           | 0.21      | Miyaji et al (1998) |
| ROSAT PSPC   | Lynx   | 0.144 | 11.5                | 0.43                                           | 0.28      | Miyaji et al (1998) |
| ASCA SIS     | Various| 0.538 | 8.9                 | 0.50                                           | 0.06      | Gendreau et al (1995) |
| ROSAT PSPC   | Various| 0.726 | 11.0                | 0.30                                           | 0.77      | Vecchi et al (1999) |
| SAX LECS+MECS| Various| 0.726 | 11.0                | 0.30                                           | 0.77      | Vecchi et al (1999) |

Table 1. Measurements of the XRB intensity at 1 keV carried out with imaging instruments.Ω

2 THE COSMIC VARIANCE

Table 1 lists the XRB intensity measurements that we have used. In particular and for each particular datum we list the measured intensity at 1 keV $I_i$, the quoted statistical 1-sigma error $\sigma_i$, the 1-sigma statistical uncertainty and $\Sigma_i$ the 1-sigma uncertainty derived when statistical and cosmic variances are included.

If the true average XRB intensity is $I_{XRB}$ then we want to compute the probability density function $P_i(I|I_{XRB})$ of obtaining an intensity $I$ in a measurement over a solid angle $\Omega$, with a statistical error $\sigma_i$. This is computed by first convolving the confusion noise distribution with the statistical noise distribution (which we assume to be gaussian) and later shifting the resulting distribution to have a mean value $I_{XRB}$. This shift can be attributed to the behaviour of the source counts in the very faint regime, which would not affect the shape of the distribution. Assuming a top-hat beam (which is appropriate for our purposes), the confusion noise distribution can be expressed as (Barcons 1992)

$$P_{con}^{conf}(I) = \int d\omega \, e^{-2\pi i \omega I} \exp(\Omega, \int dS \, N(S)[e^{2\pi i \omega S} - 1])(1)$$

where $N(S)$ is the number of sources per unit solid angle and unit flux which in the range were we shall use it ($S \sim 10^{-13} - 10^{-12}$ erg cm$^{-2}$ s$^{-1}$) can be approximated as euclidean

$$N(S) = \frac{3}{2} \frac{K}{S_0} \left( \frac{S}{S_0} \right)^{-5/2},$$

where we choose $S_0 = 10^{-14}$ erg cm$^{-2}$ s$^{-1}$ and then $K$ is the source density, extrapolated with the same euclidean law, at a flux limit $10^{-14}$ erg cm$^{-2}$ s$^{-1}$. Indeed, the value of $K$ depends on the energy band used for the observations. For the ‘hard’ X-ray measurements (ASCA and BeppoSAX) we assume an extrapolation of the Piccinotti et al (1982) source counts, now confirmed down to fluxes below $10^{-13}$ erg cm$^{-2}$ s$^{-1}$ (Cagnoni, Della Ceca & Maccacaro 1998, Gendreau et al 1998). This gives $K \sim 300$ deg$^{-2}$. For the ‘soft’ X-ray measurements we use the ROSAT normalisation $K \approx 150$ deg$^{-2}$ (Hasinger et al 1993, Branduardi-Raymont et al 1994). In modelling the confusion noise distribution for the various measurements of the XRB intensity, we have taken into account the possible excision of bright foreground sources by applying the corresponding cutoff in the flux integral of eqn. (1). This really only applies to the Chen et al (1996) ROSAT measurement where sources brighter than $3.4 \times 10^{-14}$ erg cm$^{-2}$ s$^{-1}$ were excluded. For the remaining measurements we have assumed that the sources in the Piccinotti et al (1982) catalogue had been avoided and therefore we applied a cutoff at a flux of 2-10 keV of $3 \times 10^{-14}$ erg cm$^{-2}$ s$^{-1}$.

Equation (1) ignores clustering of the XRB sources. Indeed clustering broadens the distribution of intensities with respect to a uniform distribution (Barcons 1992). From Barcons, Fabian & Carrera (1998) we see that for angular scales of the order of $\sim 1$ deg$^2$, excess fluctuations due to clustering amount to $\sim 0.5 - 1.2\%$, which implies a correction of the order of $\sim 10\%$ (at most) to the broadening computed by eq. (1). The relative amplitude of the clustering correction stays approximately constant when going to slightly smaller scales and decreases slowly when the small-scale declining part of the power spectrum of the fluctuations is reached. Given the smallness of this effect end the uncertainties in the modelling of the source clustering and its evolution we decided to ignore this small effect.

Convolving eqn. 1 with a gaussian of dispersion $\sigma_i$ and shifting the mean to a value $I_{XRB}$ gives the function $P_i(I|I_{XRB})$ where now we express $I$ and $I_{XRB}$ as monochromatic intensities at 1 keV in units of keV cm$^{-2}$ s$^{-1}$ sr$^{-1}$ keV$^{-1}$. For the conversion between monochromatic intensity and broad-band flux $S$ per unit solid angle in a given energy band we use an XRB spectral

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shape with $\alpha = 0.4$ for the ‘hard’ instruments and $\alpha = 0.7$ for the ‘soft’ instruments which result in

$$I(\text{keV cm}^{-2} \text{s}^{-1} \text{sr}^{-1} \text{keV}^{-1}) = \frac{S}{S_0} \Omega(\text{deg}^2)^{-1} \Delta^{-1}$$

(3)

where $\Delta \approx 200$ if the flux is in the 2-10 keV band and $\Delta \approx 70$ if the flux is in the 0.5-2 keV band.

Typically, the curves including the cosmic variance are much broader than the statistical error. To illustrate this, Table 1 also lists the dispersion $\Sigma$, obtained via a Gaussian fit to $P(I|I_{XRB})$ (which accounts for both the statistical and the cosmic variance) for comparison with the statistical dispersion $\sigma_I$.

We now use these distributions to compute Bayesian estimates of the true XRB intensity $I_{XRB}$. We assume an a priori distribution which is uniform over a sufficiently wide range of values of $I_{XRB}$ (5 to 16 keV cm$^{-2}$ s$^{-1}$ sr$^{-1}$ keV$^{-1}$). The probability density function for $I_{XRB}$ given a set of data is (Press 1989)

$$f(I_{XRB}) = \frac{\Pi_i P_i(I_i|I_{XRB})}{\int dI_{XRB} \Pi_i P_i(I_i|I_{XRB})}$$

(4)

where the products extend to the data points under consideration. In what follows, our $I_{XRB}$ estimates correspond to the maximum of that function, which we also use to derive 90% confidence intervals.

3 THE INTENSITY OF THE XRB

We first compute $f(I_{XRB})$ for the measurements obtained within each imaging X-ray mission separately. The results are shown in Fig. 1 where it can be seen that the various measurements with the same instrument are consistent when cosmic variance is taken into account. In particular the variety of ASCA values which have been obtained with both the SIS and GIS instruments at different epochs, does not call for extra systematic effects. The same comment applies to the ROSAT data points, as none of them is completely out of the distribution expected in terms of cosmic variance and statistical uncertainties, in spite of the fact that these intensities have been obtained with different PSPCs and/or different gains. The corresponding estimates of the XRB intensity are $9.8^{+0.7}_{-0.9}$, $11.1^{+1.0}_{-1.3}$ and $12.7^{+0.9}_{-1.9}$ keV cm$^{-2}$ s$^{-1}$ sr$^{-1}$ keV$^{-1}$ (90 per cent errors) for ASCA, BeppoSAX and ROSAT respectively.

Although there is considerable overlap between the distributions corresponding to the three missions, there are obvious systematic differences. To illustrate this we combine all the data points with the use of eqn. 4 (see Fig. 1). The fact that there are points which obviously fall outside the distribution confirms the presence of systematic differences between the missions. Indeed the largest differences occur between ASCA and ROSAT amounting to $\sim 30$ per cent.

Cross-calibration mismatches between missions have been reported by various authors, in particular between ROSAT and ASCA (e.g., Yaqoob et al 1994, Allen & Fabian 1997). Iwasawa et al (1999) addressed this point with detail, motivated by simultaneous ROSAT and ASCA observations of the Seyfert galaxy NGC 5548. They find that the ROSAT PSPC spectrum is $\Delta \alpha \sim 0.4$ steeper than the simultaneous ASCA spectrum over a similar energy band. Iwasawa et al (1999) also comment on the fact that these calibration mismatches do not occur between ASCA and any other missions, which find similar spectral shapes for a variety of objects observed.

A further complication in the combination of XRB data from various missions is the different influence of the Galaxy. The main ASCA (Gendreau et al 1995) and BeppoSAX missions together.
(Vecchi et al 1999) measurements of the XRB intensity only used events above 1 keV, where the contribution from the Galaxy is ∼ 1 per cent or less for these instruments. However, in the Hasinger (1992) ROSAT estimate, the whole 0.1-2.4 keV band was used to extract both the extragalactic and local components. For example, more than 30 per cent of the counts above 0.5 keV are of galactic origin. Although the influence of the Galaxy on the determination of $I_{X, RB}$ is uncertain in the ROSAT data, it is likely to be more important.

Excluding the ROSAT data points, a bayesian estimate of $I_{X, RB}$ yields $10.0^{+0.6}_{-0.5}$ keV cm$^{-2}$ s$^{-1}$ sr$^{-1}$ keV$^{-1}$, but the fact that the largest measured intensity is the BeppoSAX one is suggestive of residual systematic effects (see again fig. 1). In this case, however, these do not need to be larger than a few per cent.

All of the above estimates give significantly higher values for the XRB intensity than the extrapolated value of the HEAO-1 data. For the BeppoSAX and the ASCA data, the HEAO-1 value ($8.2^{+0.6}_{-1.0}$ keV cm$^{-2}$ s$^{-1}$ sr$^{-1}$ keV$^{-1}$) is still marginally consistent with the current modelling in terms of statistical and cosmic variance of the ASCA and BeppoSAX data. However, this interpretation would mean that the regions of the sky used in the imaging observations are systematically brighter than the average sky sampled by HEAO-1. The possibility that the XRB spectrum between 1 and 3 keV is steeper than the assumed $\alpha = 0.37$ (there is a hint of this in the HEAO-1 data, see the mid panel of Fig. 4a in Marshall et al 1980) does not really help to alleviate this mismatch. The reason is that both ASCA and BeppoSAX measurements are quite sensitive to photon energies $\sim 3$ keV, where the intensities found are significantly larger than the HEAO-1 result at the same energy.

4 CONCLUSIONS
Cosmic variance is able to account for the dispersion of the measured values of the extragalactic XRB intensity within the same mission. However, systematic differences remain among different missions, which cannot be understood in terms of spatial fluctuations.

A cross-calibration mismatch between ROSAT observations and those form other missions has been reported (Iwasawa et al 1999). But even using the ASCA and BeppoSAX data only the result ($10.0^{+0.6}_{-0.5}$ keV cm$^{-2}$ s$^{-1}$ sr$^{-1}$ keV$^{-1}$) is higher than the XRB intensity at 1 keV extrapolated from the HEAO-1 data at photon energies above 3 keV. A steepening of the XRB spectrum at energies below 3 keV does not really help as both ASCA and BeppoSAX are sensitive to energies $\sim 3$ keV and above where the mismatch persists. The only conclusion we can reach is that although internal calibration uncertainties in each mission amount to probably less than 10 per cent, the cross-calibration among them has still large residual errors, preventing a more precise determination of the XRB intensity.

XMM is and will be for many years the most sensitive X-ray imaging facility over the 0.1-10 keV energy band, providing also moderate spectral resolution. Over 1 year, XMM will carry out observations of 500-1000 fields of $\sim 0.2$ deg$^2$, so we expect $\sim 100$ deg$^2$ to be covered each year. The cosmic variance (roughly scaling as $\Omega^{-1/2}$) will then be small enough for unambiguous determinations of the XRB spectrum and intensity. If the EPIC instruments can be calibrated to significantly better than 10 per cent, this will certainly solve the issue of the intensity of the XRB.

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REFERENCES
Allen S.W., Fabian A.C., 1997, MNRAS, 286, 583
Barber C.R., Warwick R.S., 1994, MNRAS, 267, 270
Barcons X., 1992, ApJ, 396, 460
Barcons X., Fabian A.C., Carrera F.J., 1998, MNRAS, 293, 60
Boldt E., 1987, Phys Rep, 146, 215
Branduardi-Raymont G. et al 1994, MNRAS, 270, 947
Cagnoni I., Della Ceca R., Maccacaro T., 1998, ApJ, 493, 54
Chen L.-W., Fabian A.C., Gendreau K.C., 1996, MNRAS, 285, 449
Fabian A.C., Barcons X., 1992; ARAA, 30, 429
Gendreau K.C. et al, 1995, PASJ, 47, L5
Gendreau K.C., Barcons X., Fabian A.C., 1998, MNRAS, 297, 41
Georgantopoulos I. et al, 1996, MNRAS, 280, 276
Hasinger G., 1992, In: The X-ray background, Barcons X., Fabian A.C., eds. Cambridge University Press, p. 229
Hasinger G., Burg R., Giacconi R., Hartner G., Schmidt M., Trümper J., Zamorani G., 1993, A&A, 275, 1
Iwasawa K., Fabian A.C., Nandra K., 1999, MNRAS, 307, 611
Marshall F.E., Boldt E.A., Holt S.S., Miller R.B., Mushotzky R.F., Rose L.A., Rotschild R.E., Serlemitsos P.J., 1980, ApJ, 235, 4
Miyaji T., Ishisaki Y., Ogasa Y., Ueda Y., Freyberg M.J., Hasinger G., Tanaka Y., 1998, A&A, 334, L13
Gruber D.E., 1992, In: The X-ray background, Barcons X., Fabian A.C., eds. Cambridge University Press, p. 44
Piccinnotti G., Mushotzky R.F., Boldt E.A., Holt S.S., Marshall F.E., Serlemitsos P.J., Shafer R.A., 1982, ApJ, 253, 485
Press, S.J., 1989, Bayesian statistics: principles, models and applications, J. Wiley& Sons.
Scheuer P.A.G., 1974, MNRAS, 167, 329
Vecchi A., Molendi S., Guainazzi M., Fiore F., Parmar A.N., 1999, A&A, 349, L73
Yaqoob T., Serlemitsos P., Mushotzky R.F., Madejski G., Turner T.J., Kunieda H., 1994, PASJ, 46, L173

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