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The Cosmic X-ray Background at the Peak of its Emission: An Accurate Measurement with *BeppoSAX* and its Consequences

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Abstract We discuss an accurate measurement of the CXB in the 15–50 keV range performed with the *Phoswich Detection System (PDS)* instrument aboard the *BeppoSAX* satellite, whose results have already been recently reported elsewhere Frontera et al. (2007). After the recently reported 2–10 keV CXB measurements obtained with the imaging instruments aboard the X-ray satellites *BeppoSAX*, *XMM-Newton*, and *Chandra* that give CXB intensities systematically higher than those obtained with *HEAO–1* in the same energy band, suspects of systematic errors in the *HEAO–1* measurements at low and higher energies have been raised by several authors. Using the *BeppoSAX* PDS pointings at high galactic latitude ($|b| > 15^\circ$) we have measured the CXB spectrum and intensity level in the 15–50 keV energy band. Our results are consistent with those obtained with *HEAO–1* at the same energies. Astrophysical consequences are discussed.

Key words: X-rays: diffuse background — cosmology: diffuse radiation — cosmology: observations

1 INTRODUCTION

The cosmic X-ray background (CXB) is contributed mainly by active galactic nuclei (AGN) powered by accreting supermassive black holes at the centers of large galaxies (Setti & Woltjer 1989; Comastri et al. 1995; Gilli 2004). Optically bright quasars and Seyfert galaxies dominate at low energies (up to a few keV), while obscured AGNs, which outnumber unobscured ones by a factor 3–4 (Ueda et al. 2003; La Franca et al. 2005), are responsible for the bulk of the CXB at high energies (>10 keV). However the CXB intensity level is still a matter of debate. After the first pioneer CXB measurements (Horstman et al. 1975), the major effort to get a reliable estimate of the spectrum in a broad energy band (2–400 keV) was performed in the late 1970's with the A2 and A4 instruments aboard the first *High Energy Astronomical Observatory* (*HEAO–1*). The A2 results (3–45 keV) were first presented by Marshall et al. (1980, hereafter M80), while the final results obtained with the A4 Low Energy Detector (LED, 13–180 keV) were reported by Gruber et al. (1999, hereafter G99), who also presented the conclusive results from both experiments. According to these authors the CXB energy spectrum $J(E)$ in the 3–60 keV interval is well represented by a power-law (PL) with a high energy exponential cutoff (CUTOFFPL), while the corresponding $E\,J(E)$ spectrum shows a characteristic bell shape with a maximum intensity of 42.6 keV (cm^2 s sr)$^{-1}$ at 29.3 keV.

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After *HEAO–1* there have been many other CXB measurements at low energies (<15 keV) with both imaging and non imaging telescopes aboard satellite missions. These measurements show a low spread of the PL photon index Γ and a high spread (up to ~40%) of the CXB intensity, with the lowest CXB estimates obtained with *HEAO–1* A2 (M80) and the highest with the focusing telescopes aboard *BeppoSAX* (Vecchi et al. 1999), *XMM-Newton* (Lumb et al. 2002; De Luca & Molendi 2004) and *Chandra* (Hickox & Markevitch 2006). The 2–10 CXB estimates obtained with the collimated *Proportional Counter Array* aboard *Rossi–XTE* (Revnivtsev et al. 2003) and from the re-analysis of the *HEAO–1* A2 measurement (Revnivtsev et al. 2005), which are about 20% higher than those obtained by G99 can be made almost consistent or higher by at most 5% than those of G99 by a more reliable calibration of the flux scale Frontera et al. (2007).

At energies higher than 15 keV, the measurements performed before *HEAO*–1 show CXB estimates almost consistent (within 10%), but systematic errors in the CXB intensity estimates cannot be excluded. Churazov et al. (2007) have recently reported on measurements with *INTEGRAL*, resulting in a CXB normalization $\sim 15\%$ higher than that quoted in G99. However this result, because of the many uncertainties and assumptions, appears somewhat weak for an unbiased estimate of the CXB. Indeed Churazov et al. (2007) wish further INTEGRAL observations at other epochs in order "to verify the agreement of observations and predictions".

We performed an accurate measurement of the total (resolved plus unresolved) high energy (>15 keV) CXB intensity by exploiting the pointed observations performed with the *Phoswich Detection System* (PDS) aboard the *BeppoSAX* satellite (Boella et al. 1997). An exhaustive description of the adopted method and results are being published (Frontera et al. 2007). Here we give a summary of our measurement, we show further results and discuss their main implications.

2 CXB MEASUREMENT

2.1 Unresolved CXB

The measurement of the unresolved $\nu_{\rm CXB}$ count rate is based on the *Sky-Earth Pointing* (SEP) method, in which we subtract from the background level $\nu_B^{\rm sky}$ measured from a blank sky field ($\nu_B^{\rm sky} = \nu_{\rm CXB} + \nu_{\rm in}^{\rm sky}$) the count rate level measured when the telescope is pointing to the dark Earth ($\nu_B^{\rm Earth} = \nu_A + \nu_{\rm in}^{\rm Earth}$), where ν_A is the count rate due to the X-ray terrestrial albedo entering through the telescope FOV, and $\nu_{\rm in}^{\rm sky}$, $\nu_{\rm in}^{\rm Earth}$ are the instrumental backgrounds when pointing at the sky and at the Earth, respectively. The difference spectrum $D(E) = (\nu_{\rm CXB} - \nu_A) + (\nu_{\rm in}^{\rm sky} - \nu_{\rm in}^{\rm Earth})$ becomes $D(E) = \nu_{\rm CXB} - \nu_A$ if $\nu_{\rm in}^{\rm Earth} = \nu_{\rm in}^{\rm sky}$. In order to make sure that $\nu_{\rm in}^{\rm Earth} = \nu_{\rm in}^{\rm sky}$ we performed a careful selection of the available data, as described in Frontera et al. (2007).

In order to satisfy the blank sky field condition, we discarded all pointings within 15 ° from the Galactic plane, while for the OFF-source pointings we filtered out those observations for which the +OFF and −OFF fields could be contaminated, e.g. from serendipitous X-ray sources, fast transients or solar flares. For the ON–source pointings we accepted only those fields for which the difference between the ON-source count rate and count rate measured at either +OFF and −OFF is consistent with zero within 1σ. For other details see Frontera et al. (2007). As a result of the above selections, from the entire set of 868 *BeppoSAX* observation periods (OPs) off the Galactic plane, the number of useful OPs becomes 275 (127 ON-source, 71 +OFF-source, and 77 −OFF-source) with a total exposure time of 4031 ks. The dark Earth was observed for a total of 2056 ks.

2.2 Results

For the derivation of the CXB intensity we used the sum $D(E) = D_{\rm ON}(E) + D_{+\rm OFF}(E) + D_{-\rm OFF}(E)$, where $D_{\rm ON}(E)$, $D_{+\rm OFF}(E)$, and $D_{-\rm OFF}(E)$ are the difference spectra for the ON–source, +OFF–source and −OFF–source pointings, respectively. We found that $D_{\rm ON}(E)$, $D_{-\rm OFF}(E)$ and $D_{+\rm OFF}(E)$ are all consistent with each other within their uncertainties. $D(E)$ was well determined up to 50 keV.

We fit $D(E)$ with the difference of two model spectra, one to describe the unresolved CXB spectrum and the other to describe the albedo radiation spectrum.

For the albedo model spectrum we used a photo-electrically absorbed power–law (details in Frontera et al. 2007). To model the CXB spectrum we assumed the CXB spectral shape obtained with *HEAO–1* A2+A4 (G99). Thus we used as input models a CUTOFFPL and a PL which, in the 15–50 keV interval, still gives a good description of spectral shape. The resulting fits of the unresolved CXB are described in detail in Frontera et al. (2007). We concentrate here on the results obtained for the total CXB (unresolved plus resolved). The latter was obtained by adding to the unresolved CXB the contribution of extragalactic sources (mainly AGNs), on the basis of the serendipitous sources that were detected with the PDS (see, for details, Frontera et al. (2007)). We found that the resolved sources increase the CXB intensity by 4.7%. In Table 1 we report, for each of the used input models, the results found for the total CXB spectrum. In Figure 1 we show the best fit photon spectra compared with those obtained with other measurements.

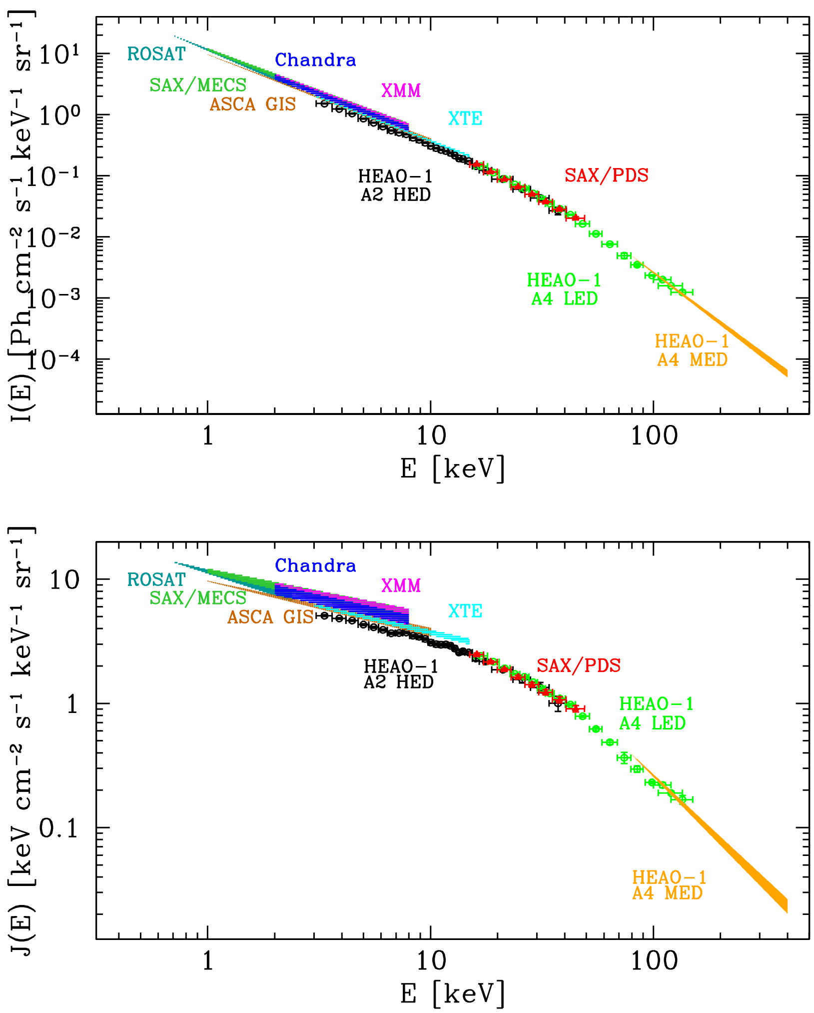

Fig. 1 Total (unresolved plus resolved) CXB spectrum, modeled with a POWERLAW, as observed with the PDS experiment (red points) compared with measurement results obtained with other missions. *Top:* CXB photon spectrum *Bottom:* CXB energy spectrum.

We have also evaluated the upper limit to the CXB intensity that can be marginally accommodated by our data, by exploring the space of all the parameters involved in the fits (details in Frontera et al. 2007). We found that, independently of the CXB model, in 90% of this multi-parameter space the $I^{\rm tot}_{\rm CXB}(20-50\ {\rm keV})$ is lower than 6.8×10^{-8} erg cm^{-2} s^{-1} sr^{-1}.

Table 1 Spectral parameters of the total (unresolved plus resolved) CXB as derived from the PDS measurement. Uncertainties are 1σ errors. The parameters frozen in the fits are shown in square parentheses.

CXB model	$N_{\rm CXB}^{\rm tot}$ ^{c}	Γ	$E_{\rm c}$ ^{d}	$\chi^2/{\rm dof}$	$I_{\rm CXB}^{\rm tot}(20-50~{\rm keV})$ ^{e}
Power-law[a]	0.100 ± 0.003	[1.98]	–	9.43/23	5.89 ± 0.19
Cutoff power-law[b]	0.158 ± 0.003	[1.4]	[41.13]	9.2/23	5.52 ± 0.18
Cutoff power-law[b]	0.167 ± 0.017	1.4 ± 0.3	[41.13]	9.0/22	5.88 ± 0.19
Cutoff power-law[b]	0.148 ± 0.002	[1.29]	[41.13]	9.2/23	5.43 ± 0.17

[a] $I_{\rm CXB}(E) = N_{\rm CXB}(E/20)^{-\Gamma}$

[b] $I_{\rm CXB}(E) = N_{\rm CXB}(E/20)^{-\Gamma}\,\exp\,(-E/E_c)$

[c] In units of photons cm^{-2} s^{-1} keV^{-1} sr^{-1}

[d] In units of keV

[e] In units of 10^{-8} erg cm^{-2} s^{-1} sr^{-1}.

3 DISCUSSION

Comparing our results shown in Table 1 with the previous ones, we find that our best fit $I_{\rm CXB}^{\rm tot}(20-50~{\rm keV})$ is in excellent agreement with that obtained with *HEAO–1* A2 (M80), and slightly lower (from 3% to 10%, depending on the input model) than that quoted by G99. The best fit value of the maximum CXB flux density is obtained in the 26–28 keV band and ranges from 39.4 to 40.2 keV (cm^2 s sr)$^{-1}$ depending on the model assumed, with a statistical uncertainty in the centroid of ± 1.5 keV (cm^2 s sr)$^{-1}$ at 90% confidence level for a single interesting parameter. In addition our upper limit is 12% higher than the best fit CXB intensity value quoted by G99 and 21% higher than that quoted by M80.

Even this upper limit disagrees with the extrapolation to higher energies of the low energy (<10 keV) CXB estimates obtained with the focusing telescopes aboard *BeppoSAX* (Vecchi et al. 1999), *XMM–Newton* (Lumb et al. 2002; De Luca & Molendi 2004), and *Chandra* (Hickox & Markevitch 2006). Thus, if the CXB spectral shape derived with *HEAO–1* is correct as assumed, our results raise the issue about the origin of the highest CXB intensities being quoted at lower energies. We discuss this point in Frontera et al. (2007) with the likely conclusion that the highest 2–10 keV CXB estimates could be mostly due to systematic errors in the response functions used for the diffuse emission (e.g., an underestimate of the stray light).

Independently of the CXB intensity issue at lower energies, our observational findings bear at least two important astrophysical consequences. Firstly, they provide a robust estimate of the accretion driven power integrated over cosmic time, including that produced by the most obscured AGNs. It should be noted that the highest CXB intensities claimed at low energies, frequently assumed to imply an upward renormalization of the HEAO–1 spectrum. would entail a much larger number (a factor 2–3) of Compton thick AGNs (Gilli et al. 2007) than that implied by our results: a present black hole mass density of $\sim 3 \times 10^5\ M_\odot$ Mpc^{-3}, using an admittedly uncertain bolometric correction of 30 for the 15–50 keV band and an efficiency of 0.1 in converting gravitational into radiation energy.

Secondly, under the assumption that the *HEAO–1* spectral shape (G99) applies down to 2 keV, we find that the summed contribution of the observed X-ray source counts in the 2–10 keV band is consistent with the found upper limit in the PDS CXB intensity level, if the error associated with the source count evaluation (Moretti et al. 2003) is taken into account. As a consequence, our measurement suggests that it is quite possible that almost all the CXB in the 3–8 keV band has already been resolved into sources down to the faintest fluxes of the *Chandra* deep fields.

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