

# Large-scale variations of the cosmic X-ray background and the X-ray emissivity of the local Universe

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## ABSTRACT

We study the cosmic X-ray background (CXB) intensity variations on large angular scales using the slew data from the RXTE observatory. We detect intensity variations up to  $\sim 2\%$  on angular scales of  $20\text{--}40^\circ$ . These variations are partly correlated with the local large-scale structure, which allowed us to estimate the emissivity of the local Universe in the energy band  $2\text{--}10$  keV at  $(8 \pm 4) \times 10^{38} h_{75} \text{ erg s}^{-1} \text{ Mpc}^{-3}$ . The spectral energy distribution of the large-angular-scale variations is hard and is compatible with that of the CXB, which implies that normal galaxies and clusters of galaxies, whose spectra are typically much softer, do not contribute more than 15% to the total X-ray emissivity of the local Universe. Most of the observed CXB anisotropy (after exclusion of point sources with fluxes  $\geq 10^{-11} \text{ erg s}^{-1} \text{ cm}^{-2}$ ) can be attributed to low-luminosity AGNs.

**Key words.** galaxies: active – galaxies: Seyfert – galaxies: statistics – X-rays: galaxies – X-rays: general

## 1. Introduction

The Universe is a bright source of X-ray emission. The first discovery in X-ray astronomy was that of the brightest source in the X-ray sky – the accreting neutron star Sco X-1 – along with an isotropic cosmic X-ray background (Giacconi et al. 1962), which was later shown to be composed of emission from a large number of discrete extragalactic sources (Giacconi et al. 1979).

Virtually all astrophysical objects produce X-ray emission: starting from numerous ordinary stars, with typical X-ray ( $2\text{--}10$  keV) luminosities  $L_x \sim 10^{27}\text{--}10^{30} \text{ erg s}^{-1}$ , through accreting white dwarfs ( $L_x \sim 10^{30}\text{--}10^{34} \text{ erg s}^{-1}$ ), neutron stars and black holes ( $L_x \sim 10^{35}\text{--}10^{38} \text{ erg s}^{-1}$ ), to active galactic nuclei (AGNs) and quasars ( $L_x \sim 10^{40}\text{--}10^{46} \text{ erg s}^{-1}$ ).

The bulk of the cosmic X-ray background (CXB) is created by AGNs with luminosities  $\sim 10^{42}\text{--}10^{45} \text{ erg s}^{-1}$  (e.g. Ueda et al. 2003), but a non-negligible contribution to the CXB must be provided by low-luminosity ( $L_x \sim 10^{40}\text{--}10^{42} \text{ erg s}^{-1}$ ) AGNs, which constitute the majority of active supermassive black holes in the local Universe (see e.g. Elvis et al. 1984; Ho et al. 1997), as well as by ordinary galaxies, due to their populations of X-ray binaries and stars. Unfortunately, it is difficult to estimate the cumulative luminosities of these faint extragalactic sources simply by counting them, as is usually done for powerful AGNs. Indeed, a normal galaxy or a low-luminosity AGN with an X-ray luminosity  $\sim 10^{40} \text{ erg s}^{-1}$  located at a redshift typical of CXB sources ( $z \sim 1\text{--}2$ ) will produce an X-ray flux less than  $10^{-17} \text{ erg s}^{-1} \text{ cm}^{-2}$ , which cannot be detected by existing X-ray telescopes. However, the cumulative emissivity of all weak sources can in principle be estimated using measurements of the CXB (e.g. Boldt 1992).

It has long been understood that the properties of CXB sources are not constant but have evolved with cosmic time

(e.g. Longair 1966; Schmidt 1968; Silk 1968; Maccacaro et al. 1983, 1991). In particular, the cumulative X-ray volume emissivity of AGNs was much higher at redshifts of  $z \sim 1\text{--}2$  than it is at the present time (e.g. Maccacaro et al. 1983; Barger et al. 2005), the star-formation rate (and the associated rate of X-ray production) was similarly higher (Madau et al. 1996), and so on. It is therefore clear that the integrated X-ray emissivity of a unit volume or of a unit mass of Universe has evolved with time, so knowing its local ( $z = 0$ ) value is essential for understanding the evolution of different populations of X-ray sources, in particular supermassive black holes in the centers of galaxies.

Even the latest all-sky surveys conducted at energies above 2 keV (Revnivtsev et al. 2004; Markwardt et al. 2005; Krivonos et al. 2007b), with their sensitivity  $\sim 10^{-11\text{--}11.5} \text{ erg s}^{-1} \text{ cm}^{-2}$ , can detect sources with luminosities  $\leq 10^{41} \text{ erg s}^{-1}$  only at distances smaller than 10 Mpc, which is not enough to obtain a representative sample of such objects and to estimate their cumulative luminosity. Stacking of individually undetectable fluxes from nearby low-luminosity X-ray sources can hardly help, because the number density of such sources increases with decreasing luminosity not fast enough ( $LdN/d\log L \propto L^{-(\lesssim 1)}$ , see e.g. Elvis et al. 1984; Persic et al. 1989) to compensate for the rapidly declining signal-to-noise ratio.

However, it has been realized that the CXB can help in estimating the total X-ray emissivity of the local Universe (e.g. Schwartz 1980; Warwick et al. 1980; Shafer & Fabian 1983; Jahoda et al. 1991; Miyaji et al. 1994; Carrera et al. 1995; Scharf et al. 2000). The idea is quite simple – the Universe has large-scale structure characterized at zero redshift by a factor of a few or larger density contrast on scales of tens of Mpc. Since X-ray sources are expected to trace the overall matter distribution, they

should exhibit a similar space density contrast. When observed in an X-ray survey, the cumulative emission of all individually undetectable sources located in an overdense region of the local Universe will create an area of enhanced sky surface brightness on top of the nearly isotropic X-ray background emission created at larger distances. The amplitude of this large angular scale enhancement of the CXB intensity can be converted into a value of the cumulative volume emissivity of faint X-ray sources, provided that one knows the distribution of matter density in that local region of the Universe and the so-called bias factor of X-ray sources (i.e. the ratio of fractional X-ray source number density fluctuations to fractional matter density fluctuations).

Recent advances in the understanding of the bias factor of AGNs indicate that in the nearby Universe ( $z \sim 0$ ) it is close to unity (see e.g. Tegmark & Peebles 1998; Boughn & Crittenden 2004). Arguably the most direct determination of the bias factor (specifically, a measurement of the ratio of fractional number density variations of X-ray sources to fractional number density variations of IRAS infrared-selected galaxies) was recently made using the INTEGRAL all-sky hard X-ray survey (Krivonos et al. 2007b), and the AGN bias factor was confirmed to be close to unity. This implies that to convert CXB intensity variations into an X-ray emissivity of the local Universe we can use any good tracer of mass density in the local volume, for instance infrared galaxies (see e.g. Basilakos & Plionis 2006). Supporting evidence that AGNs closely trace the distribution of galaxies was recently presented by Li et al. (2006) based on an optically selected sample of narrow-line AGNs from the Sloan Digital Sky Survey.

According to the current knowledge of the distribution of matter in the local Universe, even its largest angular scale anisotropy – the dipole component – continues to grow to distances  $\geq 100$ –200 Mpc (e.g. Rowan-Robinson et al. 1990; Kocevski et al. 2004; Basilakos & Plionis 2006), where the distribution of matter is not yet well known. Nonetheless, there are distinct density patterns in the nearest ( $\lesssim 30$ –70 Mpc) Universe that should be imprinted into the CXB intensity distribution and could be studied with the available X-ray data.

In this paper we essentially repeat the analysis of large-scale anisotropies of the CXB that was previously performed based on HEAO1/A2 data (e.g. Shafer & Fabian 1983; Jahoda et al. 1991; Miyaji et al. 1994; Scharf et al. 2000; Boughn et al. 2002), using a newly available dataset from the PCA instrument aboard RXTE and redetermine the X-ray emissivity of the local ( $z = 0$ ) Universe utilizing the advantages of the higher collective area of RXTE/PCA and its smaller field of view (and consequently the reduced confusion noise).

Throughout the paper we adopt a Hubble constant  $H_0 = 75 h_{75} \text{ km s}^{-1} \text{ Mpc}^{-1}$  and recalculate all relevant quantities from cited papers to this reference value.

## 2. Data analysis

### 2.1. Systematic limitations

The high level of isotropy of the cosmic X-ray background was noticed already shortly after its discovery (e.g. Schwartz 1970). In order to detect and accurately measure the anisotropy of the CXB caused either by our motion with respect to the outer Universe where the bulk of the CXB is created (the so-called Compton-Getting, or CG effect, Compton & Getting 1935) or by the large-scale structure of the Universe at zero redshift, one should reach an accuracy of measuring the CXB intensity of 0.1–0.5% of its average level.

Indeed, the relative dipole-like ( $\delta I/I \propto 1 + \Delta \cos \theta$ ) variations of the CXB intensity due to our motion with respect to the outer Universe radiation field (the cosmic microwave background, CMB) are expected to be (see e.g. Scharf et al. 2000) on the order of

$$\Delta_{\text{CG}} = (v/c)(\Gamma + 2) \sim 4.2 \times 10^{-3},$$

where  $\Gamma \approx 1.4$  is the photon index of the CXB in the RXTE/PCA effective energy band 3–20 keV.

The X-ray dipole due to large-scale structure in the local Universe, produced by inhomogeneities in the matter density distribution at distances  $D_{\text{LSS}} \lesssim 50$ –100 Mpc, is expected to be

$$\Delta_{\text{LSS}} \sim \frac{\phi_{z=0} D_{\text{LSS}}}{4\pi I_{\text{CXB}}} \sim (0.6 - 1) \times 10^{-2},$$

where  $\phi_{z=0} \sim 10^{39} \text{ erg s}^{-1} \text{ Mpc}^{-3}$  is the average volume emissivity of the local Universe and  $I_{\text{CXB}} \sim 7 \times 10^{-8} \text{ erg s}^{-1} \text{ cm}^{-2} \text{ sr}^{-1}$  is the average CXB intensity in the 2–10 keV energy band.

Such accuracy presents a challenge for a vast majority of X-ray instruments. One of the best instruments suitable for measuring the tiny large-scale CXB anisotropies was the A2 experiment aboard the HEAO1 observatory (Rothschild et al. 1979). It had a special design of detectors that made it possible to subtract the internal background of the detectors with almost absolute accuracy. However, its detectors had relatively large fields of view ( $1.5^\circ \times 3^\circ$ ,  $3^\circ \times 3^\circ$  and  $3^\circ \times 6^\circ$ ) and therefore seriously suffered from the confusion noise produced by sources with flux below the detection threshold.

The field of view of the RXTE/PCA spectrometer is significantly smaller ( $\sim 0.974 \text{ sq deg}$ ), while its effective area is significantly larger ( $\sim 6400 \text{ cm}^2$  of all the detectors combined, or  $\sim 1300 \text{ cm}^2$  of a single detector), and the model of the PCA detector background developed by the PCA team allows one to subtract it with an accuracy of at least 2–3% of the CXB intensity (Jahoda et al. 2006). Therefore, RXTE/PCA is currently the best instrument for studying large-scale anisotropies of the CXB.

The noise created by point sources with flux just below the detection threshold is still an issue for RXTE/PCA. Its influence can be estimated as follows (see e.g. Warwick et al. 1980). Suppose that the differential number-flux function of point sources  $dN(S)$  is isotropic over the sky and can be described by a power law with a slope of  $-5/2$ :

$$dN(S) = \Omega A S^{-5/2} dS,$$

where  $S$  is the source flux,  $A$  is a normalization constant and  $\Omega$  is the solid angle subtended by the survey. In reality the number-flux function of extragalactic sources flattens below  $10^{-14} \text{ erg s}^{-1} \text{ cm}^{-2}$  (e.g. Hasinger et al. 1993; Vikhlinin et al. 1995), but this does not strongly change the following estimates.

The number of sources in any infinitely small flux bin is subject to Poisson statistics, hence we can write for the dispersion of the integrated signal:

$$(\delta I)^2 = \int_{S_{\text{min}}}^{S_{\text{max}}} S^2 \frac{dN}{dS} dS \approx 2\Omega A S_{\text{max}}^{1/2},$$

where  $S_{\text{max}}$  is the maximal flux of undetected sources.

The relative uncertainty in the flux from the solid angle  $\Omega$  will be  $\delta I/I \propto S_{\text{max}}^{1/4}/\Omega^{1/2}$ . For the real number-flux function of extragalactic sources in the energy band 2–10 keV ( $A \approx 0.015 \text{ deg}^{-2} (10^{-11} \text{ erg s}^{-1} \text{ cm}^{-2})^{3/2}$ , see e.g. Revnivtsev et al. 2004), this will be

$$\left(\frac{\delta I}{I}\right)_{\Omega} \approx 8.7 \times 10^{-2} S_{\text{max},11}^{1/4} \Omega_{\text{deg}}^{-1/2}. \quad (1)$$

Here  $S_{\max,11}$  is the maximal flux of sources in units of  $10^{-11} \text{ erg s}^{-1} \text{ cm}^{-2}$ , and  $\Omega_{\text{deg}}$  is the solid angle of the survey in degrees. We adopted the CXB intensity in the 2–10 keV to be equal to  $1.95 \times 10^{-11} \text{ erg s}^{-1} \text{ cm}^{-2} \text{ deg}^{-2}$  (Revnivtsev et al. 2003, 2005, see also more on this below).

From the above estimates it is clear that in order to reach the required accuracy of  $(1-5) \times 10^{-3}$  of the CXB intensity one needs to exclude sources with fluxes down to  $\sim 10^{-11} \text{ erg s}^{-1} \text{ cm}^{-2}$  and average CXB intensity measurements over areas of  $\sim 1000 \text{ deg}^2$ .

The sensitivity of the RXTE Slew Survey varies across the sky due to the non-uniform exposure map. Therefore, strictly speaking the limiting flux for source detection is not the same in different parts of the sky. However, more than 60% of the sky is covered with sensitivity better than  $10^{-11} \text{ erg s}^{-1} \text{ cm}^{-2}$  and nearly all of the remaining sky is covered down to  $2.5 \times 10^{-11} \text{ erg s}^{-1} \text{ cm}^{-2}$  (2–10 keV).

Given the sensitivity map of the survey, we can estimate variations in the X-ray flux that can be resolved into point sources in a given region of the sky if we assume an isotropic distribution of sources over the sky with the number flux function described above:

$$I_{\text{resolved}} = \int_{\Omega} \int_{S_{\min}}^{\infty} S N(S) dS d\Omega / \Omega.$$

The resulting distribution of  $I_{\text{resolved}}$  values averaged over cones with  $25^\circ$  half-open angle (solid angle 1932 sq deg) is roughly Gaussian and has a width ( $1\sigma$ )  $\sim 0.5\%$  of the mean CXB intensity.

Therefore, despite the non-uniform coverage of the sky with RXTE/PCA slews, the adopted method of data reduction allows for secure sky cleaning, which should not create any significant artificial structures on the map of the CXB intensity measured over large solid angles.

## 2.2. RXTE/PCA slew data

Over its lifetime (Dec. 1995–present), the spectrometer PCA on the RXTE observatory has collected a lot of data during slews between pointed observations. The high collective area of the PCA detectors ( $\sim 1300 \text{ cm}^2$  of each of the five) makes it possible to detect sources down to fluxes  $\sim 5 \times 10^{12} \text{ erg s}^{-1} \text{ cm}^{-2}$  and this detection limit is determined solely by the confusion noise (Markwardt & Swank 2004; Revnivtsev et al. 2004).

For our analysis we used all publicly available data of RXTE/PCA scans and slews from February, 1996 till February 8, 2007. During a significant period of RXTE operations only some of the five PCA detectors were switched on (this mode of operations became dominant after the end of Epoch3 of the PCA voltage, i.e. since March 1999), therefore not all of the PCA detectors have collected sufficient exposure time and sky coverage for our purposes. For this reason, in our analysis we used only detector #2, which collected  $\sim 6-6.5$  Ms of data between February, 1996 and February 8, 2007 (we consider here only regions away from the Galactic plane,  $|b| > 14^\circ$ , and  $> 3^\circ$  away from the detected point sources reported in Revnivtsev et al. 2004).

We analyzed the data of the first layer (which typically enables the highest signal-to-noise ratio for weak X-ray sources) of the PCU2 in two energy bands, 3–8 and 8–20 keV, which were converted into instrumental channels using response matrices (constructed with the HEASOFT 6.0 package) appropriate for each observation. We similarly analyzed observations of the

Crab nebula, 6 background pointings (see Jahoda et al. 2006) and “dark” Earth<sup>1</sup>.

Flux measurements by RXTE/PCA are subject to systematic uncertainties. Absolute flux measurements (in particular those of the CXB) depend on how well the effective area of the detector is known, the knowledge of the effective solid angle of the collimator and so on. In our analysis we relied on an absolute X-ray flux calibrator – the Crab nebula. Specifically, our results are obtained under the assumption that the Crab spectrum is  $dN/dE = 10E^{-2.05}$  (which implies a flux in the 2–10 keV energy band  $F_{\text{Crab}} = 2.39 \times 10^{-8} \text{ erg s}^{-1} \text{ cm}^{-2}$ ).

As we are interested in low X-ray intensity variations over the sky we should take into account all systematic uncertainties that could affect our measurements at the level of a per cent or so.

Our data analysis consists of the following steps:

- Background subtraction using standard HEASOFT 6.0 tasks. Aggressive filtering of PCA data: based on electron counts (ELECTRON < 0.08), Earth elevation angle (ELV > 10), of  $3^\circ$ -radius regions around known detected point sources (Revnivtsev et al. 2004) and new source candidates (we have filtered out all sky cells of  $\sim 1.5^\circ \times 1.5^\circ$  size where more than  $5\sigma$  count rate excesses were detected), and of a wide band around the Galactic plane (see more on this in Sect. 2.6).
- Correction for the low “unmodeled” part of the RXTE/PCA background.
- Correction for PCA detector parameters’ drifts based on measurements of the Crab count rates in the considered energy bands.
- Additional check of the accuracy of all corrections by studying the time dependence of the flux measured from dark Earth, which in the case of the RXTE/PCA background model = – the CXB flux (the standard PCA background subtraction procedure applied to dark Earth observations result in a flux that is equal to that of the CXB, but with a negative sign). Here we assume that dark Earth emits zero X-ray flux in the studied energy band, because the reflectivity of the Earth atmosphere is small at these energies (even though it may be significant at energies above 15–20 keV) (Churazov et al. 2006) and the cosmic ray-induced atmospheric hard X-ray radiation is still strongly photoabsorbed at these energies (Sazonov et al. 2007). In addition, we check the time dependence of the contrast between fluxes collected from spatially distinct regions of sky.
- Estimation of the contribution of the Galaxy to the sky X-ray intensity at high Galactic latitudes.

Below we describe these steps in more detail.

## 2.3. Background subtraction

One of the main systematic uncertainties of relative flux measurement is the accuracy of the PCA background subtraction. The currently standard approach to this consists of modeling the background with the highest possible accuracy using a number of tracers recorded onboard on the 16-s time scale and verifying that “empty” sky regions have zero intensity after background subtraction. Although the CXB contribution to the flux measured

<sup>1</sup> An observation was considered to be pointed at dark Earth if the angle between the vector Sun-Earth and the vector directed from the center of Earth towards the point on its surface observed by RXTE/PCA is larger than  $90^\circ$  and the RXTE/PCA field of view is directed more than  $10^\circ$  below the Earth’s limb.

by RXTE/PCA is eliminated by this procedure, it can be recovered by observations of dark Earth (see e.g. Revnivtsev et al. 2003).

The current version of RXTE/PCA software (LHEASOFT 6.0) provides an outstandingly accurate model of the instrumental background (L\_7\_240CM version of the background), which allows for an accuracy of background subtraction of a few per cent, i.e. the root-mean-square amplitude of the unmodeled deviations is  $\sim 0.02\text{--}0.03$  cts/s/PCU/beam in the 3–8 keV energy band, which corresponds to  $\sim 3 \times 10^{-13}$  erg s $^{-1}$  cm $^{-2}$  deg $^{-2}$  for a Crab-like spectrum (e.g. Markwardt et al. 2002; Jahoda et al. 2006, see also Fig. 1), or  $\sim 2\text{--}3\%$  of the average CXB intensity.

However, as our aim is to measure the CXB intensity with an accuracy of 0.1–0.5%, we made special corrections to take into account the unmodeled part of the RXTE/PCA background, taking advantage of the observational fact that this part appears to be an additive component to all measured count rates irrespective of the pointing of a given PCA observation. As an example of such a behavior, we show in Fig. 1 background subtracted, 4-month-binned count rates averaged over the whole sky, over the cone of 25° half-opening angle around  $(l, b) = (130^\circ, 40^\circ)$  and over the 6 RXTE/PCA pointings that were used to calibrate the PCA background model. The similarity of the patterns of the unmodeled parts of the background in these three cases is apparent.

If we assume that the true intensity averaged over the whole sky is zero at relatively high Galactic latitudes  $|b| > 25^\circ$  (to eliminate the contribution from the Galactic ridge X-ray emission, see Sect. 2.6) and also excluding 3° regions around detected point sources, the 4-month-averaged measurements of sky intensity provide us an estimate of the unmodeled part of the RXTE/PCA background, which we add to the model-predicted rates of the PCA background.

In our subsequent analysis we only used data obtained later than  $10^8$  RXTE seconds (i.e. after March 3rd, 1997), because only during this period more than 3 background pointings were used to calibrate the PCA background model, which apparently has an effect on the accuracy of the background subtraction (see Fig. 1).

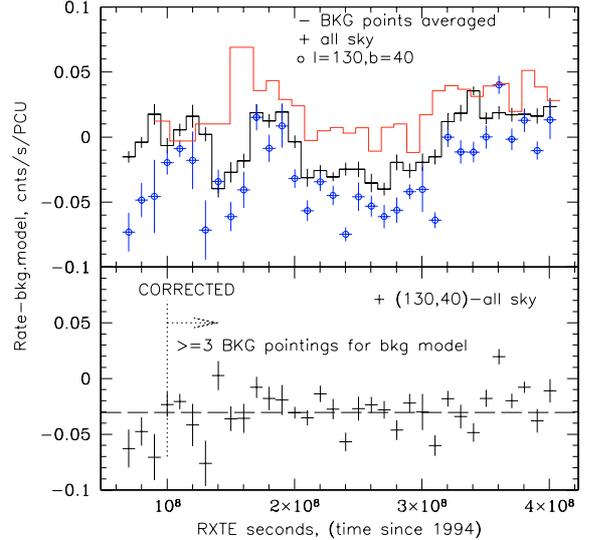
The effect of the additional background subtraction is demonstrated in the lower panel of Fig. 1. We see that the two-step background subtracted sky intensity from some sky region is much more stable than that obtained after just the first (standard) step and that the variations of the inferred intensity are almost compatible with the statistical uncertainties of the measurements.

#### 2.4. Drift in the detector parameters

Another important issue in X-ray flux measurement is the parameters of the detector. The efficiency of the PCA detectors slightly changed during the large time span considered here (1996–2007) for different reasons, including slow drift of the energy scale of the detectors and a slight change of the gas purity or pressure within the signal volumes (see e.g. Jahoda et al. 2006).

This small ( $\sim 5\%$ ) drift of the detector effective area manifests itself in the measured count rates from the Crab, a constant X-ray source which has been regularly observed by RXTE (see Fig. 2). We made a special correction for this effect, modeling it by a piecewise function.

In order to check the stability of the corrected count rates we studied the detector count rate during dark-Earth observations. By construction, the PCA background model eliminates the



**Fig. 1.** *Upper panel:* background subtracted intensities of sky, averaged over 4-month intervals. Crosses denote all-sky averaged values, open circles the intensity integrated over a 25°-radius circle around  $(l, b) = (130^\circ, 40^\circ)$  and the solid line the intensity averaged over the 6 RXTE/PCA background pointings. It can be seen that all three curves demonstrate similar variations with time, which we consider the unmodeled part of the RXTE/PCA instrumental background. *Lower panel:* background subtracted intensity from  $(l, b) = (130^\circ, 40^\circ)$  with the all-sky-averaged value subtracted. The unmodeled intensity variations have become much lower and are almost compatible with the statistical uncertainties.

count rate during off-bright-source observations, automatically subtracting the average CXB flux contribution. Observations of dark Earth therefore allow one to see this oversubtracted part of the PCA background, which is essentially the all-sky average CXB flux (see Revnivtsev et al. 2003). The count rates measured during dark-Earth observations, corrected for all the above effects, are shown in Fig. 2. We see that the resulting dark-Earth count rate ( $= -\text{CXB flux}$ ) is stable to within  $\sim 0.5\text{--}1\%$ .

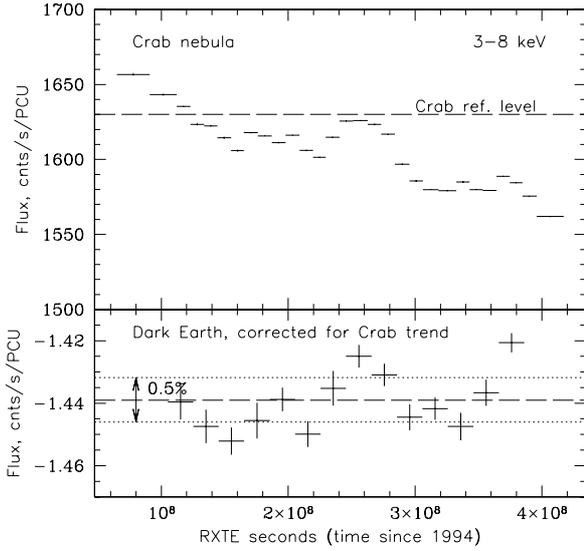
Similar corrections were done in the energy channel 8–20 keV.

After all the corrections, the CXB intensity measured within relatively large sky areas (so that the Poisson variance of the number of unresolved sources within a given area does not influence the result) exhibits definite variations over the sky. We studied the time dependence of these variations to check for any remaining systematic effects in our data. The difference in the CXB intensity between various sky regions revealed no systematic variations ( $\sigma_{\text{systematic}} < 0.01$  cts/s/PCU, see Fig. 3).

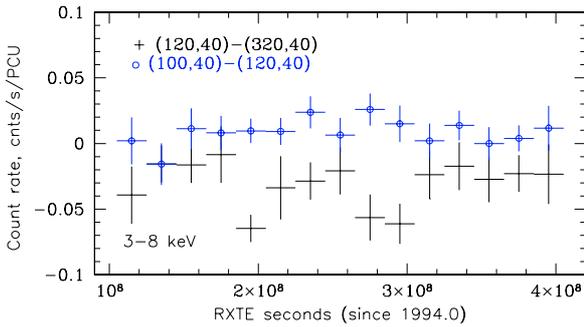
#### 2.5. CXB intensity

As a byproduct of the analysis described above we have estimated the CXB intensity in two broad energy channels ( $= -\text{dark Earth flux}$ ). The averaged CXB fluxes measured by PCA in the bands 3–8 keV and 8–20 keV are  $0.847 \pm 0.008$  mCrab/beam and  $1.43 \pm 0.05$  mCrab/beam, respectively. Note that in making these estimates we adopted that the average deadtime fraction during Crab observations is  $\sim 4\%$  higher than that during empty sky/dark Earth observations (see e.g. Jahoda et al. 2006).

For a power-law spectral shape of the CXB with a photon index  $\Gamma = 1.4$  the flux measured by PCA in the energy band



**Fig. 2.** *Upper panel:* background subtracted count rate of the Crab nebula measured in the energy band 3–8 keV with RXTE/PCA over its lifetime. The count rate is not corrected for the deadtime fraction which is typically ~4% higher during Crab observations than during off-source observations. *Lower panel:* background subtracted count rate of dark Earth corrected for the “unmodeled” background and for the drift of the detector parameters.



**Fig. 3.** Differences of the count rates integrated over a 25°-radius circle around different  $(l, b)$  positions at various epochs (approximately 4-month averaged): between  $(120^\circ, 40^\circ)$  and  $(320^\circ, 40^\circ)$  – crosses, and between  $(100^\circ, 40^\circ)$  and  $(120^\circ, 40^\circ)$  – open circles. It can be seen that these differences are quite stable with time and apparently not strongly affected by systematic effects. The uncertainty caused by the Poisson variations of the number of unresolved point sources within the considered regions (see Eq. (1)) is  $\sim 1.5 \times 10^{-3}$  cnts/s/PCU.

3–8 keV corresponds to a flux at 2–10 keV of  $(1.95 \pm 0.02) \times 10^{-11}$  erg s $^{-1}$  cm $^{-2}$  beam $^{-1}$ . Taking into account that the effective solid angle of the PCA spectrometer is  $\sim 0.974$  sq deg, we find that the average CXB intensity  $I_{\text{CXB}, 2-10 \text{ keV}} = (2.00 \pm 0.02) \times 10^{-11}$  erg s $^{-1}$  cm $^{-2}$  deg $^{-2}$ .

## 2.6. Contribution of the Galaxy

Our Galaxy is a bright emitter in soft (e.g. McCammon & Sanders 1990), standard (e.g. Worrall et al. 1982; Revnivtsev et al. 2006) and hard X-rays (e.g. Krivonos et al. 2007a). Due to the large angular scale of this emission, it can contribute to the large-scale anisotropy of the CXB and therefore this contribution should be estimated and subtracted or masked.

The operating energy band of RXTE/PCA (3–20 keV) precludes a detection of the soft X-ray background of the Galaxy, hence only the Galactic ridge X-ray emission (GRXE) is important for our study.

It was recently shown that most likely the GRXE is a superposition of weak Galactic sources, namely cataclysmic variables and coronally active stars, and that its surface brightness closely follows the near-infrared (NIR) surface brightness of the Galaxy (Revnivtsev et al. 2006). Therefore, one can estimate the ridge X-ray intensity in a given direction by rescaling the NIR map of the Galaxy.

However, due to the discrete nature of the GRXE one should not expect to see this emission in regions of extremely low surface number density of stellar objects, such as the Galactic poles. Indeed, if we assume the volume emissivity distribution of Galactic X-ray emission to be  $\phi(z) = dL_x/dV \sim 1.5 \times 10^{26} \exp(-z/z_0)$  erg s $^{-1}$  pc $^{-3}$  with the exponential scale height  $z_0 \sim 130$  pc (Revnivtsev et al. 2006), the flux from a solid angle  $\Omega$  in the direction of the Galactic poles ( $|b| = 90^\circ$ ) will be

$$F = \int_0^\infty \frac{\phi(z)\Omega z^2 dz}{4\pi z^2} \sim 2 \times 10^{-9} \frac{\Omega}{4\pi} \text{ erg s}^{-1} \text{ cm}^{-2}.$$

For a 1 sq deg solid angle, the flux will be  $\sim 5 \times 10^{-14}$  erg s $^{-1}$  cm $^{-2}$ , i.e.  $\sim 0.25\%$  of the CXB flux. Some addition from the stellar population of the bulge of our Galaxy (Bahcall 1986) can be anticipated, however it will not be larger than that of the disk.

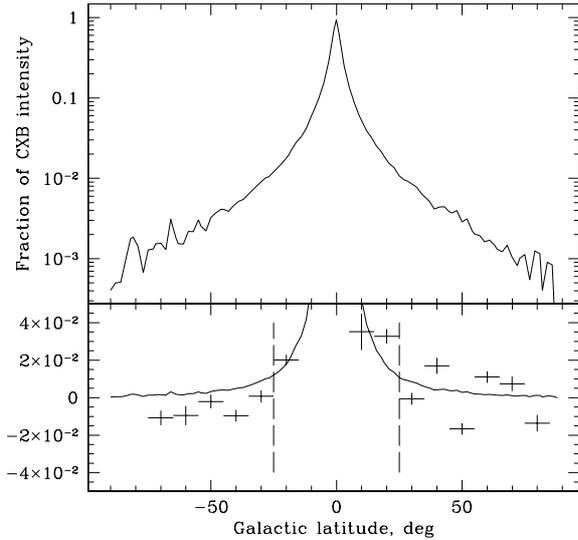
However, in reality the GRXE flux from these directions should be even lower because sources creating the GRXE are expected to be quite rare there. Indeed, in the direction of the Galactic poles the mass of stars in the solid angle  $\Omega$  is (here we assume for simplicity an exponential distribution of stellar density in the Galactic disk,  $\rho(z) = \rho_0 \exp(-z/z_0)$ , the stellar density in the Solar vicinity being  $\rho_0 = 0.04 M_\odot/\text{pc}^3$ , Robin et al. 2003)

$$M(b) = \int_0^\infty \frac{\rho_0 e^{-z/z_0} \Omega z^2}{|\sin^3 b|} dz = \frac{2\rho_0 \Omega z_0^3}{|\sin^3 b|} \\ \sim 50 M_\odot \text{ for } |b| = 90^\circ \text{ and } \Omega = 1 \text{ sq deg.}$$

Such a small stellar population will simply not contain any X-ray sources, such as cataclysmic variables, which create the bulk of the GRXE at energies 3–20 keV. Indeed, more than 50% of the GRXE is created by sources with luminosities  $> 10^{30}$  erg s $^{-1}$  (Sazonov et al. 2006; Revnivtsev et al. 2007), whose density is smaller than  $10^{-3} M_\odot^{-1}$ . Therefore, more than  $M_{\text{lim}} > 10^3 M_\odot$  of stars are needed to create significant X-ray flux from the studied direction. Such a mass in a  $\Omega \approx 1$  sq deg solid angle will be present if  $|\sin^3(b)| \lesssim 2\Omega\rho_0 z_0^3/M_{\text{lim}}$ , i.e. for  $|b| \lesssim 20^\circ$ . Nonetheless, for rough estimates of the GRXE contribution one can use the scaled (as shown in Revnivtsev et al. 2006) brightness of the Galaxy at  $3.5 \mu\text{m}$  (see Fig. 4).

After all the filterings we constructed an X-ray intensity profile of the sky along the Galactic latitude, by averaging measured intensities over  $|l| < 40^\circ$  (Fig. 4). At latitudes  $|b| > 25^\circ$  no dependence of the sky surface brightness on latitude exceeding the involved uncertainties is seen, hence we mask the wide  $|b| < 25^\circ$  region from our subsequent analysis.

We note that the signal previously seen at  $25^\circ < |b| < 60^\circ$  by HEAO1/A2 (Iwan et al. 1982) may be created by unresolved Galactic and extragalactic sources for which the HEAO1/A2 instrument was less sensitive than PCA due to the wider field of view of the former and consequently higher confusion noise. This is supported by the fact that Iwan et al. (1982) claimed the



**Fig. 4.** *Upper panel:* latitudinal (at  $|l| < 40^\circ$ ) profile of X-ray (3–8 keV) surface brightness of the Galaxy, obtained by rescaling the NIR map of the sky (Revnivtsev et al. 2006), presented in units of the average CXB intensity in the 3–8 keV energy band. The value of the NIR sky brightness at the Galactic poles has been subtracted. The small variations of the NIR intensity at  $|b| > 50^\circ$  are due to weak point sources present in the studied areas. It can be seen that at  $|b| > 25^\circ$ , the contamination of the CXB by the Galaxy is smaller than  $\sim 1\%$ . In reality it should drop much faster at  $|b| > 20^\circ$  due to the discrete nature of the GRXE (see text). *Lower panel:* the same profile is shown in linear scale along with real measurements of the X-ray (3–8 keV) intensity at  $|l| < 40^\circ$ . All the flux measurements were corrected following the prescriptions described in Sect. 2. The dashed lines denote the area ( $|b| < 25^\circ$ ) that was excluded from the subsequent analysis of the CXB maps due to the apparent non-negligible contribution of Galactic X-ray emission.

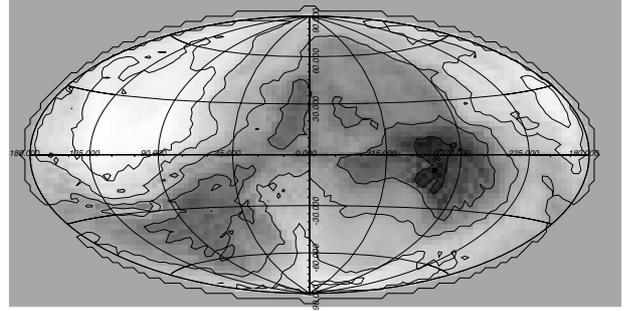
Galactic background emission to be present at  $|l| > 90^\circ$  at a level comparable to that at  $|l| < 90^\circ$ , while the latest studies show that there is virtually no GRXE emission from the Galactic anticenter region (Revnivtsev et al. 2006).

### 3. Results

#### 3.1. Large-scale structure of the local Universe

The Universe is highly homogeneous on large scales ( $\gg 100$ –200 Mpc, e.g. Wu et al. 1999). Due to this uniformity and because most of the CXB originates at relatively large distances from us (at redshifts  $z \sim 1$ –2, e.g. Ueda et al. 2003; Hasinger et al. 2005), the CXB is very isotropic. However, at smaller distances the Universe becomes inhomogeneous and this should cause some anisotropies of the CXB intensity. Since the CXB is composed of discrete sources, these anisotropies should be studied on angular scales sufficiently large that the Poisson variations of the number of sources within the area of study are unimportant, as described by Eq. (1).

The dipole component of the CXB intensity caused by the local large-scale structure saturates at distances  $D \lesssim 200$ –300 Mpc (e.g. Scharf et al. 2000; Kocevski et al. 2004). However, higher order harmonics might be created by more distant structures. This fact can significantly complicate the comparison of the CXB anisotropies with the structures in the nearby Universe known from sky surveys (e.g. the well-known IRAS PSCz survey in the infrared band, Saunders et al. 2000), because



**Fig. 5.** Adaptively smoothed map of the CXB intensity in the 3–8 keV energy band, in Galactic coordinates. Plotted is the X-ray intensity averaged over cones with half opening angles 20–40°, excluding areas around point sources and a band around the Galactic plane ( $|b| < 25^\circ$ ). The contours represent the levels of deviations of the CXB intensity from its average value by  $-1\%$ ,  $-0.5\%$ ,  $0\%$ ,  $0.5\%$  and  $1\%$ .

typically such structures are well probed only out to distances  $\sim 100$ –200 Mpc.

In order to study the amplitude of CXB anisotropies that may be created by more distant structures we analyzed the distribution of galaxies resulting in the semi-analytic modeling of formation of galaxies in the Millennium simulation (De Lucia & Blaizot 2007). It was shown (e.g. Wang et al. 2007) that the distribution of  $z \approx 0$  galaxies in this simulation has statistical properties that resemble those of the real populations of galaxies in the local Universe. Our examination of the distribution of simulated galaxies showed that the matter density structures at distances  $> 100$ –200 Mpc create fluctuations of the CXB intensity comparable in amplitude with those created by the more nearby mass concentrations. Therefore, one should anticipate only a partial correlation of the CXB intensity map with that of the nearest mass concentrations.

#### 3.2. CXB intensity maps and dipole component

After implementing all the masks and corrections (see the previous section), we constructed maps of sky intensity (with the average CXB intensity subtracted as a consequence of the PCA background subtraction) in the energy bands 3–8 keV (Fig. 5) and 8–20 keV.

The simplest all-sky anisotropy that can be studied using these maps is the CXB dipole component.

A simple determination of the dipole component of the CXB angular distribution – its approximation by the function  $I/I_0 = 1 + \Delta \cos \theta$  (where  $\theta$  is the angle between a given direction and the direction of the dipole) – yields the amplitude  $\Delta$ . The obtained parameters of the CXB dipole in the 3–8 keV energy band are presented in Table 1.

Several effects can produce a dipole component of the cosmic X-ray background. First, it may arise from some primordial anisotropy of the Universe at high redshifts.

Second, the observed CXB dipole must contain a contribution from the Doppler effect associated with our motion with respect to the reference frame in which the bulk of the CXB emission is produced ( $z \sim 1$ –2).

Finally, relatively nearby ( $z < 0.1$ –0.5) mass concentrations can impose their imprints on the CXB map and, in particular, create a non-negligible dipole component. According to our current understanding of the distribution of matter density in the nearby Universe, it indeed contains a dipole component

**Table 1.** Parameters of the CXB dipole component in the energy band 3–8 keV determined from RXTE/PCA data.

Map	Amplitude ( $\Delta$ , $10^{-3}$ )	$l(^{\circ})$	$b(^{\circ})$
All sky	$10.4 \pm 0.5$	$294 \pm 20$	$8 \pm 6$
CG corrected	$8.1 \pm 0.9$	$333 \pm 21$	$2 \pm 7$

that causes a bulk motion of the local group of galaxies, which in turn can be seen via measurements of the dipole component in the map of the cosmic microwave background (see e.g. Rowan-Robinson et al. 1990).

As dipole anisotropy is a very wide feature on the sky, it is very hard to disentangle in the CXB intensity map the different components of the total dipole signal described above.

One promising approach would be to study the dependence of the amplitude of CXB intensity variations on energy. Indeed, as was already mentioned in Sect. 2.1, the amplitude of the Compton-Getting dipole component (caused by our motion with respect to the CXB reference frame) has a strong dependence on the slope of the CXB spectrum in the considered energy band:  $\delta I/I \propto \Gamma(E) + 2$ , where  $\Gamma(E)$  is the characteristic power-law photon index of the spectrum at energy  $E$ . This means that in hard X-rays (50–200 keV), where the CXB spectrum has a much steeper slope  $\Gamma \sim 2.2$ – $2.6$  than at energies below  $\sim 20$  keV ( $\Gamma \sim 1.4$ ), the amplitude of the CG effect must be considerably higher and have a specific energy dependence. On the other hand, the spectrum of the CXB dipole component created by large-scale structures in the nearby Universe is expected to be similar to that of the cumulative emission spectrum of local X-ray sources (mainly AGNs), which resembles the CXB spectrum blueshifted by a factor of  $\sim 2.5$  (Sazonov et al. 2008). Therefore, the relative amplitude of this dipole component must also be approximately constant below  $\sim 20$  keV and growing at higher energies, but the energy dependence is expected to be different from that of the CG dipole.

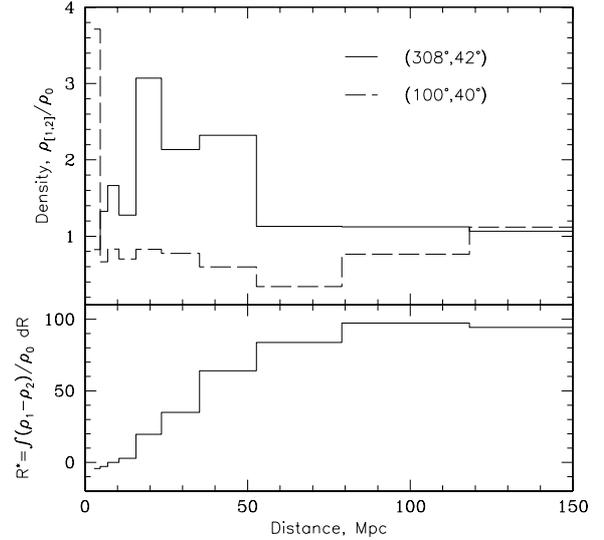
Unfortunately, within the RXTE energy band we cannot distinguish the CG dipole from the large-scale structure one. Therefore, in our analysis we estimated the CG dipole based on the known parameters of our motion with respect to the cosmic microwave background (Lineweaver et al. 1996).

In Table 1 we present the measured CXB dipole in the energy band 3–8 keV and its value after subtraction of the CG component. We note that the obtained dipole amplitude and orientation are in good agreement with the values determined from the analysis of HEAO1/A2 data (Scharf et al. 2000).

### 3.3. X-ray emissivity of the local Universe

In order to compare the CXB intensity variations with the expected variations due to the nearby mass concentrations, we made use of the IRAS PSCz survey of galaxies (Saunders et al. 2000). The underlying assumption of our analysis below is that X-ray emitting AGNs trace the underlying mass distribution approximately as well as IRAS galaxies, i.e. the relative bias factor between the two classes of objects is close to unity. As discussed in the Introduction, this has been shown to be the case at least on large distance scales.

The difference in the distribution of nearby ( $< 100$ – $200$  Mpc) galaxies in a pair of directions will cause a difference in the CXB intensities in these directions. Suppose that the X-ray emissivity per unit number density of galaxies is constant ( $\psi = dL/dN = \text{const.}$ ), whereas the space density of galaxies ( $\rho = dN/dV$ ) varies with direction and with distance from us ( $R$ ). Let

**Fig. 6.** Space density of IRAS galaxies calculated in two directions of the sky within cones with a half-opening angle of  $25^{\circ}$  (upper panel) and the radially integrated difference of these densities (lower panel).

the density of galaxies in one direction be  $\rho_1(R)$  and in another  $\rho_2(R)$ . Then the difference of the CXB fluxes  $\Delta F$  created by the density variations, measured within a solid angle  $\Omega$  in these directions will be

$$\Delta F = \int_0^{R_{\max}} \frac{(\rho_1 - \rho_2)\psi\Omega R^2 dR}{4\pi R^2} = \frac{\Omega\psi}{4\pi} \int_0^{R_{\max}} (\rho_1 - \rho_2) dR$$

or

$$\Delta F = \frac{\Omega\psi\rho_0}{4\pi} \int_0^{R_{\max}} \left( \frac{\rho_1}{\rho_0} - \frac{\rho_2}{\rho_0} \right) dR,$$

where  $\rho_0$  is the space density of galaxies averaged over a large volume. The value  $\psi\rho_0 = \phi$  is the X-ray volume emissivity of the local Universe in units of  $\text{erg s}^{-1} \text{Mpc}^{-3}$ . Substituting in the above formula the average density  $\rho_0$  for  $\rho_2(R)$ , we can construct a map of predicted relative deviations of the CXB intensity from its average level, generated by local ( $\leq 150$  Mpc) inhomogeneities.

We estimated the space density of IRAS galaxies with luminosities  $> 10^8 L_{\odot}$  from the PSCz catalog by taking into account the dependence of the minimum detectable galaxy luminosity on distance and the finite sky coverage of the survey.

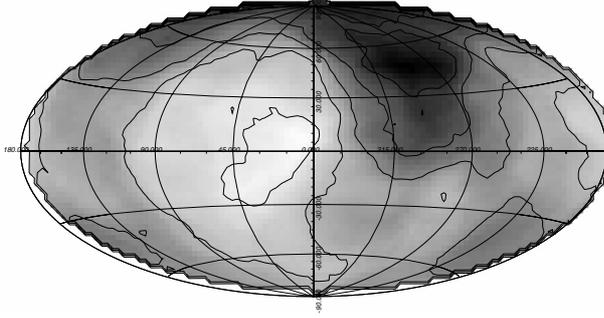
In doing that we assumed that the density of galaxies averaged over the entire sky does not depend on distance from us. As we are interested in relative galaxy densities  $\rho/\rho_0$ , we have made the most straightforward correction for the distance dependence of the minimum detectable galaxy luminosity: compared the number of detected galaxies within a given solid angle  $\Omega$  at given distance  $R$  with that averaged over the whole sky:

$$\frac{\rho}{\rho_0}(R, \Omega) \equiv \frac{N([R, R + dR], \Omega)}{N([R, R + dR], \text{All sky})}.$$

An account for the finite sky coverage of the survey was made with the help of a mask, created from the PSCz catalog data.

We only considered density variations out to a radius of  $\sim 150 h_{75}^{-1}$  Mpc.

Figure 6 shows the radially integrated difference  $\int (\rho_1 - \rho_2)/\rho_0 dR$  between the IRAS galaxy number densities in two particular directions, determined within cones with a half-opening



**Fig. 7.** Radially integrated relative space density of galaxies ( $R^* = \int (\rho_1 - \rho_0)/\rho_0 dR$ ), measured in cones with a half-opening angle of  $25^\circ$ .

angle of  $25^\circ$ . Figure 7 shows an all-sky map of relative galaxy number density variations  $R^* = \int (\rho - \rho_0)/\rho_0 dR$ , calculated in similar  $25^\circ$  cones. It can be seen that mass concentrations in the nearby Universe create a clear excess in the upper-right part of the map, which resembles the peculiarity on the CXB intensity map (Fig. 5). Due to the much smaller contrast of  $R^*$  values in the southern Galactic hemisphere, its correlation with the CXB intensity map provides very little information in addition to the northern hemisphere. Therefore, in studying the infrared-X-ray correlation we only considered the northern hemisphere.

In Fig. 8 we show a scatter plot of relative variations of the CXB intensity (3–8 keV) with respect to relative number density variations of nearby galaxies across the sky. There is marginal evidence of a correlation between these two quantities.

Since we have filtered out sources with X-ray flux larger than  $F_{\text{lim}}$  from the all-sky map, the linear part of this correlation provides us an estimate of the cumulative emissivity of sources with luminosities  $L < L_{\text{lim}} = 4\pi F_{\text{lim}} \langle D \rangle^2$ , where  $F_{\text{lim}}$  is the typical sensitivity of the survey, and  $\langle D \rangle$  is the characteristic distance at which inhomogeneities in the galaxy distribution are probed (see e.g. Fig. 6). We note that after we added new RXTE data, the typical sensitivity  $F_{\text{lim}}$  of our survey has slightly improved with respect to the value reported by Revnivtsev et al. (2004) and is now  $\sim 10^{-11}$  erg s $^{-1}$  cm $^{-2}$  for Crab-like spectra in the energy band 2–10 keV. This translates into a limiting luminosity  $L_{\text{lim}} \sim 1\text{--}3 \times 10^{42}$  erg s $^{-1}$  for  $\langle D \rangle = 30\text{--}50$  Mpc, the distances at which most of the local anisotropy is created (see Fig. 6).

Thus we find from the linear part of the correlation shown in Fig. 8 that the cumulative emissivity of local sources with  $L < L_{\text{lim}}$  is  $(4.4 \pm 3.9) \times 10^{38}$   $h_{75}$  erg s $^{-1}$  Mpc $^{-3}$  in the energy band 2–10 keV.

On the other hand, the cumulative X-ray emissivity of nearby AGNs with higher luminosities ( $L \gtrsim 10^{42}$  erg s $^{-1}$ ) has been measured fairly accurately by directly counting sources (e.g. Piccinotti et al. 1982; Ueda et al. 2003; Sazonov & Revnivtsev 2004). Taking into account that in the 3–20 keV band the cumulative emission of such AGNs is characterized by a spectral slope similar to that of the CXB, i.e.  $\Gamma \sim 1.4$  (Sazonov et al. 2008), we can convert the emissivity in the 3–20 keV band reported by Sazonov & Revnivtsev (2004) to 2–10 keV $^2$ :  $dL/dV(\log L > 42) = (4.5 \pm 0.9) \times 10^{38}$   $h_{75}$  erg s $^{-1}$  Mpc $^{-3}$ .

Adding up the contributions of sources with luminosities below  $\sim 10^{42}$  erg s $^{-1}$  and AGNs with luminosities over

$\sim 10^{42}$  erg s $^{-1}$ , estimated above, we find that the total X-ray emissivity of the local Universe in the energy band 2–10 keV is  $(9 \pm 4) \times 10^{38}$   $h_{75}$  erg s $^{-1}$  Mpc $^{-3}$ .

In reality, the limiting luminosity depends on the distance to sources and also on the direction in the sky (due to the non-uniform exposure map of the RXTE Slew Survey). Therefore, to do a more accurate estimate of the X-ray volume emissivity of the nearby Universe, ideally it would be better not to exclude bright sources from the analysis and correlate total (due to both weak and bright sources) flux variations with the integrated density contrast of galaxies. However, bright sources in the real sky would introduce strong Poisson-like noise in the sought correlation. To circumvent this problem and in an attempt to obtain a more accurate estimate of the total local X-ray emissivity, we evaluated the contribution of bright sources (which are luminous AGNs with  $L_x \gtrsim 10^{42}$  erg s $^{-1}$ ) by integrating their known luminosity function rather than by summing up the observed fluxes of really detected sources.

To this end, we adopted the shape of the luminosity function of bright ( $L_x \gtrsim 10^{42}$  erg s $^{-1}$ ) AGNs as we have measured it using the RXTE Slew Survey (Sazonov & Revnivtsev 2004), whereas the normalization of the luminosity function was taken to be proportional to the matter density as traced by IRAS galaxies, with the constraint that the total emissivity in the 2–10 keV energy band averaged over the local Universe is  $dL/dV(\log L_x > 42) = (4.5 \pm 0.9) \times 10^{38}$   $h_{75}$  erg s $^{-1}$  Mpc $^{-3}$ .

Thus, we calculated the contribution of bright sources according to the formula:

$$\Delta F_{\text{excl}} = \frac{\Omega}{4\pi} \int_0^{R_{\text{max}}} \left( \frac{\rho_1}{\rho_0} - \frac{\rho_2}{\rho_0} \right) \phi(L_{\text{lim}}) dR,$$

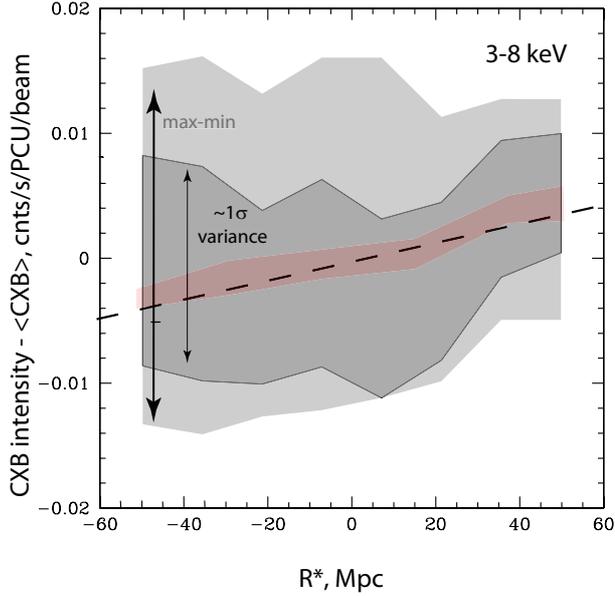
where  $\phi(L_{\text{lim}}) = \int_{L_{\text{lim}}}^{\infty} L dN$  is the cumulative emissivity of sources with luminosities  $L > L_{\text{lim}} = 4\pi R^2 f_{\text{lim}}$ . The resulting correlation of the predicted flux variations due to bright AGNs with the integrated density contrast of galaxies  $R^*$  is shown in Fig. 8 by the red area. The linear part of the correlation of total flux variations (the sum of the linear parts of the correlations for bright and faint sources) gives us an estimate of the total X-ray volume emissivity of the local Universe:  $dL/dV = (8 \pm 4) \times 10^{38}$   $h_{75}$  erg s $^{-1}$  Mpc $^{-3}$ , which is in good agreement with the more simple estimate obtained above.

Here we would like to mention one more time that the exact values of X-ray emissivity of the local Universe obtained here are affected by the variability of our sensitivity for point sources removal over the sky (see e.g. Sect. 2.1). However, even adopting the most conservative flux limit for point sources removal we obtain the value of the local Universe X-ray emissivity within the quoted  $1\sigma$  confidence interval.

### 3.4. Spectrum of variations

The simple estimates presented in Sect. 2.1 suggest that, due to the discrete nature of the CXB, variations of the CXB flux on different angular scales should have different energy spectra. Indeed, on small angular scales (e.g. 1 sq deg), Poisson variations of the number of unresolved sources (with flux below the detection threshold) dominate and one should expect that a few sources within the field of view of the detector will provide a dominant contribution to such variations. Therefore, the count rate variations will have spectral hardness typical of such ( $f \sim 10^{-12\text{--}12.5}$  erg s $^{-1}$  cm $^{-2}$ ) sources and will have the amplitude given by Eq. (1).

<sup>2</sup> Note that we here take into account a recently realized correction for flux “leakage” due to the fast motion of the PCA field of view during RXTE slews: the fluxes of point sources reported by Revnivtsev et al. (2004) were underestimated by a factor of 1/0.7 (Sazonov et al. 2008).

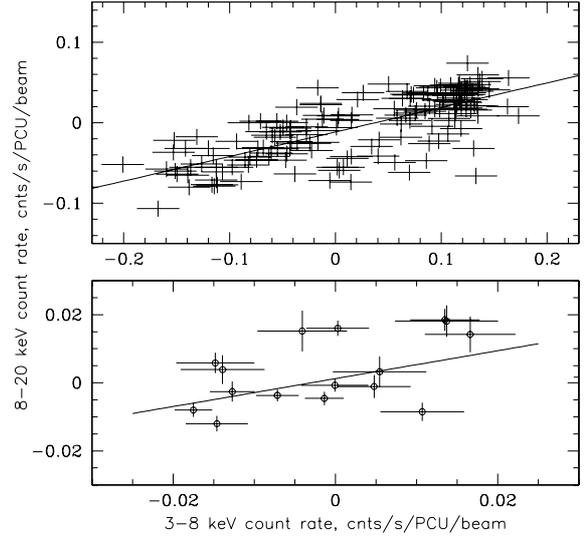


**Fig. 8.** Distribution of CXB variations measured by RXTE/PCA in the energy band 3–8 keV in beams of size 1932 sq deg (cones with a 25° half-open angle), as a function of radially integrated relative number densities of IRAS galaxies ( $R^* = \int (\rho - \rho_0)/\rho_0 dR$ ) calculated in the same beams. The dashed line shows the best-fit linear correlation between these two quantities:  $I/(\text{cnts/s/PCU/beam}) = \text{const.} + (7.7 \pm 7.0) \times 10^{-5} R^*/\text{Mpc}$ . The red area shows the correlation between  $R^*$  and the flux variations produced by the bright sources excluded from our analysis, expected based on the AGN luminosity function measured with RXTE (Sazonov & Revnivtsev 2004).

After filtering our bright sources and averaging the resulting count rates over areas of the sky  $\gg 1$  sq deg, one should expect that the spectrum of the variations will have a shape typical for the total emissivity of the local Universe (Sazonov et al. 2008), since the majority of the CXB flux variations on such angular scales are produced by large-scale mass structures in the nearby Universe (note that we have subtracted the estimated contribution of the CG dipole).

As we show in Fig. 9, the slope of the scatter plot of flux variations (with respect to the average CXB intensity) measured in PCA (1 sq deg) beams in the 3–8 and 8–20 keV energy bands is  $0.31 \pm 0.02$ , which corresponds to the hardness ratio of a power-law spectrum with a photon index  $\Gamma = 1.8 \pm 0.1$ . For comparison, the slope of the scatter plot of flux variations measured over larger solid angles ( $\sim 2000$  sq deg) is  $0.42 \pm 0.07$ , which corresponds to the hardness ratio of a power law with a photon index  $\Gamma = 1.4 \pm 0.2$ . Therefore, we do find an indication that unresolved sources with flux below the RXTE detection threshold have softer spectra than the CXB (see a similar result obtained using GINGA data in Butcher et al. 1997).

Another important conclusion that can be drawn from this RXTE/PCA measurement of the spectrum of large-angular-scale variations is that *the total X-ray emission of the local Universe is characterized by spectral hardness similar to that of the CXB*. This in particular implies that emission from non-active galaxies and clusters of galaxies, which is typically much softer than the CXB, does not significantly contribute to the total X-ray emissivity of the local Universe. Assuming that the cumulative spectral energy distribution of non-active galaxies and low-luminosity ( $L_x < 10^{42}$  erg s $^{-1}$ ) clusters of galaxies is characterized by a hardness ratio (8–20 keV over 3–8 keV) that



**Fig. 9.** Scatter plot of count rates in the energy bands 3–8 and 8–20 keV measured within the field of view of RXTE/PCA during its observations of the 6 background pointings at different times (*upper plot*), and of fluxes averaged over different wide (25° half-opening angle) cones after application of all the data filterings. The solid lines show the corresponding best-fit linear correlations. The average CXB flux has been subtracted from the count rates in both energy channels.

corresponds to a power law with a photon index  $\Gamma > 2.5$  in the energy band 3–20 keV, we can estimate that such objects contribute less than 15% of the total emissivity of the local Universe. This is consistent with our estimates presented below that are based on the statistics of local non-active galaxies and clusters of galaxies.

### 3.5. Low-luminosity objects in the local Universe

As we summarize in Table 2 and detail below, it seems possible to explain the total emissivity of sources with luminosities  $\log L_{2-10 \text{ keV}} < 42$ , estimated above from the correlation of the CXB anisotropies with the local large-scale structure, as a superposition of contributions from known types of sources: low-luminosity AGNs, clusters of galaxies, normal and starforming galaxies.

#### 3.5.1. Low-luminosity AGN

AGNs with X-ray luminosities below  $10^{42}$  erg s $^{-1}$ , which we refer to below as low-luminosity AGNs (LLAGNs) are known to be abundant in the local Universe (e.g. Ho et al. 1997). Elvis et al. (1984) used a sample of optically selected LLAGNs to estimate the X-ray luminosity function of such objects by converting their measured  $H_\alpha$  luminosities to X-ray luminosities under the assumption of linear correlation between these two quantities. These authors concluded that the cumulative emissivity of LLAGNs is  $\sim 3 \times 10^{38} h_{75} \text{ erg s}^{-1} \text{ Mpc}^{-3}$ , i.e. comparable to that of AGNs with higher luminosities.

#### 3.5.2. Clusters of galaxies

The X-ray emission from clusters of galaxies is typically fairly soft, especially from low-luminosity (low-mass) clusters. Therefore, the cumulative emissivity of clusters of galaxies must strongly depend on the energy band of the study. We consider

**Table 2.** Emissivities (2–10 keV) of different types of low-luminosity objects ( $L_{2-10\text{ keV}} < 10^{42}$  erg s $^{-1}$ ) in the local Universe in units of  $10^{38} h_{75} \text{ erg s}^{-1} \text{ Mpc}^{-3}$ .

Class	$dL/dV$
LLAGN	$\sim 3$
Clusters of galaxies	$\leq 0.1$
Starforming galaxies (HMXBs)	0.2–0.3
Normal galaxies (LMXBs)	0.2–0.4
Sum of the above	$\sim 4$
This paper, ( $\log L_{2-10\text{ keV}} \lesssim 42$ )	$4.4 \pm 3.9$

here the standard X-ray energy band 2–10 keV, where the cumulative emissivity of clusters of galaxies can be estimated from their soft X-ray luminosity function (e.g. Böhringer et al. 2002; Mullis et al. 2004) using the well-known intracluster gas temperature-luminosity relation (e.g. Markevitch 1998). We find that clusters with luminosities below  $10^{42}$  erg s $^{-1}$  in the energy band 2–10 keV contribute together  $\lesssim 10^{37} h_{75} \text{ erg s}^{-1} \text{ Mpc}^{-3}$  to the local X-ray emissivity.

### 3.5.3. Normal and starforming galaxies

The contribution of normal and starforming galaxies to the X-ray emissivity in the energy band 2–10 keV mainly comes from low-mass and high-mass X-ray binaries (LMXBs and HMXBs), respectively. The shape of the luminosity function of LMXBs is approximately constant while its normalization is proportional to the galaxy mass (e.g. Fabbiano 1986; Gilfanov 2004). Therefore, the cumulative emissivity of normal galaxies can be estimated from the known value of integrated stellar mass density ( $\Omega_* h \sim (1.6-3.5) \times 10^3$ , i.e.  $\rho_* = (2.4-5.2) \times 10^8 h_{75}^3 M_\odot \text{ Mpc}^{-3}$ ) in the low-redshift Universe (Cole et al. 2001; Kochanek et al. 2001). This gives a value of  $(2-4) \times 10^{37} h_{75} \text{ erg s}^{-1} \text{ Mpc}^{-3}$ .

The emissivity of starforming galaxies in the energy band 2–10 keV (due to HMXBs) can be estimated either via the luminosity function of nearby starforming galaxies (e.g. Ranalli et al. 2005), or by converting the average star formation rate in the local Universe (e.g. Gallego et al. 1995) to an X-ray volume emissivity using known statistical properties of HMXBs in starforming galaxies (e.g. Gilfanov et al. 2004). Both types of estimate suggest that the emissivity is approximately  $(3-4) \times 10^{37} h_{75} \text{ erg s}^{-1} \text{ Mpc}^{-3}$ .

## 4. Summary

Using data collected by the PCA instrument during slews of the RXTE observatory between its pointed observations in 1996–2007 we have obtained an all-sky map of the cosmic X-ray background intensity. Through a careful data analysis we measured the CXB intensity variations with an accuracy  $\sim 0.5\%$ .

On small angular scales we detected variations with  $\sim 7\%$  FWHM, which are most likely caused by Poisson variations of the number of weak sources below the detection threshold in the field of view of the detector.

Upon application of different filters, we detected statistically significant variations of the CXB intensity on the 20–40° angular scales with an amplitude  $\sim 2\%$ . Part of these variations is correlated with mass concentrations in the nearby ( $D < 150$  Mpc) Universe, which allowed us to make an estimate of the total emissivity of low-luminosity ( $\log L_{2-10\text{ keV}} \lesssim 42$ ) sources. The obtained value is in agreement with those determined previously

based on HEAO1/A2 data (Jahoda et al. 1991; Miyaji et al. 1994). We note that these authors studied correlations on smaller angular scales and had to deal with complications due to the strong influence of Poisson statistics and clustering of sources.

The spectral hardness ratio of large-angular-scale variations of the CXB intensity is compatible with that of the average CXB spectrum. This allowed us to put an upper limit on the combined contribution of soft X-ray sources (normal and starforming galaxies, and low-mass clusters of galaxies) to the total emissivity of the local Universe in the energy band 2–10 keV:  $< 15\%$ . Most of the observed CXB anisotropy can be attributed to low-luminosity AGNs.

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