A new method for determining the sensitivity of X-ray imaging observations and the X-ray number counts

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ABSTRACT
We present a new method for determining the sensitivity of X-ray imaging observations, which correctly accounts for the observational biases that affect the probability of detecting a source of a given X-ray flux, without the need to perform a large number of time-consuming simulations. We use this new technique to estimate the X-ray source counts in different spectral bands (0.5–2, 0.5–10, 2–10 and 5–10 keV) by combining deep pencil-beam and shallow wide-area Chandra observations. The sample has a total of 6295 unique sources over an area of 11.8 deg$^2$ and is the largest used to date to determine the X-ray number counts. We determine, for the first time, the break flux in the 5–10 keV band, in the case of a double power-law source count distribution. We also find an upturn in the 0.5–2 keV counts at fluxes below about 6 $\times$ 10$^{-17}$ erg s$^{-1}$ cm$^{-2}$. We show that this can be explained by the emergence of normal star-forming galaxies which dominate the X-ray population at faint fluxes. The fraction of the diffuse X-ray background resolved into point sources at different spectral bands is also estimated. It is argued that a single population of Compton thick active galactic nuclei (AGN) cannot be responsible for the entire unresolved X-ray background in the energy range 2–10 keV.

Key words: methods: data analysis – methods: miscellaneous – methods: statistical – surveys – X-rays: diffuse background – X-rays: galaxies.

1 INTRODUCTION
X-ray observations have complex instrumental effects that have a strong impact on the detection probability of point sources. The size and the shape of the point spread function (PSF), for example, vary across the detector. Also, the mirrors of X-ray telescopes are more efficient at collecting photons from sources close to the centre of the field of view (vignetting). This loss of sensitivity effectively translates to a reduction of the exposure time with increasing off-axis angle. In addition to the instrumental effects above, the application of any source detection software on an X-ray image also introduces biases (e.g. Kenter & Murray 2003; Wang 2004). Brighter sources have a higher probability of detection compared to fainter ones. Background fluctuations result in spurious detections that are inevitably present, hopefully in small numbers, in any X-ray catalogue. Statistical variations of the source counts combined with the steep log N $-$ log S of the X-ray population result in brighter measured fluxes for the detected sources compared to their intrinsic ones (Eddington bias). This effect becomes more severe close to the detection threshold of a given X-ray observation.

For a wide range of applications, it is important to quantify these effects accurately in order to understand the type of sources a given X-ray observation is (or is not) sensitive to. For example, the large-scale structure of X-ray sources is often estimated using the angular or the spatial correlation functions (e.g. Basilakos et al. 2004, 2005; Gilli et al. 2005; Miyaji et al. 2007). For this exercise, one needs to construct a simulated comparison sample of sources with random spatial distribution across the surveyed area. These mock catalogues should follow the same instrumental and source detection related biases as the real sample. If not any recovered signal will be heavily contaminated. Also, for the estimation of the luminosity function of X-ray selected populations, one needs to determine the volume of the survey which is accessible to a source with a particular flux and spectral shape (e.g. Hasinger, Miyaji & Schmidt 2005; Nandra, Laird & Steidel 2005a; Aird et al. 2008). Understanding the sensitivity of a given X-ray observation to active galactic nuclei (AGN) of variable obscuration and luminosity is of key importance for studies of the diffuse X-ray background (XRB; e.g. La Franca et al. 2005; Akylas et al. 2006; Gilli, Comastri & Hasinger 2007). Finally, in order to constrain the number density of X-ray sources to the faintest fluxes accessible to a given observation, it is essential to have an accurate estimate of the total surveyed area over which a source of a given flux can be detected (e.g. Kim 2007a).

The point source selection function of a given X-ray observation can be represented in the form of a sensitivity map, which should
provide an estimate of the probability that a source with a flux $f_X$ in a certain energy band will be detected across the detector. One approach to construct such a map is to perform a large number of ray-tracing simulations (e.g. Cappelluti et al. 2007; Kim 2007a). Artificial sources with a wide range of fluxes are placed at different pixels on the detector assuming a realistic model for the (instrumental and cosmic) background. The fraction of sources picked up by the detection method as a function of detector position and flux provides an estimate of the sensitivity of the particular observation. This approach, however, is time consuming and difficult to apply to large numbers of observations with different setups. These simulations cannot also fully correct for the Eddington bias, at least not for individual sources. This problem has been addressed recently by Kenter & Murray (2003) who presented a novel method for the construction of X-ray number counts that account for both the Eddington bias of individual detections and the variable point source detection threshold across the survey area. Wang (2004) further developed this technique to avoid the need for cumbersome ray-tracing simulations.

In this paper, we extend these previous studies by presenting an improved method for constructing point source sensitivity maps for X-ray imaging observations. The backbone of our approach is the point source detection method presented by Nandra et al. (2005b). Combined together, these two techniques provide a simple and efficient way of detecting sources and determining accurately their selection function self-consistently by taking into account both instrument-specific effects and the source detection biases. As a demonstration of our method, we present the X-ray number counts in different energy bands, 0.5–2, 0.5–10, 2–10 and 5–10 keV. Future applications include the determination of the angular correlation function of X-ray sources and the estimation of the luminosity function of AGN. Finally, our method is build around Chandra data but can be easily extended to XMM–Newton.

2 SOURCE DETECTION

The point source detection method has a central role in the construction of sensitivity maps. The adopted approach is fully described by Nandra et al. (2005b) and has recently been extended to use a new set of PSFs generated by MARX (Model of AXAF Response to X-rays) as discussed in Laird et al. (2008). Elliptical apertures are used to estimate the Encircled Energy Fraction (EEF) as a function of semimajor axis radius. However, for the source detection and sensitivity map construction, we use circular apertures with areas equal to that of the 70 per cent EEF ellipses. The uncertainty introduced by this approximation is <2 per cent. The source extraction is based on pre-selection of positive fluctuations using the wavelet task of CIAO at a low-probability threshold of $10^{-4}$. The total counts (source and background) at the position of each candidate source are then extracted using a circular area equal to the 70 per cent EEF elliptical aperture. The mean expected background within the detection cell is determined by scaling the counts from a local annulus centred on the source with inner aperture equal to 1.5 times the 90 per cent EEF radius and width of 50 arcsec. The probability that the candidate source is a random fluctuation of the background is estimated assuming Poisson statistics. A threshold of $<4 \times 10^{-6}$ is adopted for a source candidate to be considered a detection. At this level, about 0.5 false sources per Chandra image are expected (Laird et al. 2008). This method is simple and efficient, resulting in a higher sensitivity and fewer spurious detections compared to alternative wavelet-based only techniques. However, the most important feature of the method is that the detection cell has a fixed size at each position on the detectors, making the construction of the sensitivity maps straightforward.

3 SIMULATIONS

We use MARX to simulate Chandra observations and to validate the method for constructing sensitivity maps. MARX is a suite of programs that perform detailed ray-tracing simulations to determine how Chandra responds to astrophysical sources. In this study, we simulate point sources in the 2–10 keV spectral band with a built-in distribution per unit X-ray flux interval, $\mathrm{d}N/\mathrm{df}_X$, that follows a double power law of the form

$$\frac{\mathrm{d}N}{\mathrm{d}f_X} = \begin{cases} K \left( \frac{f_X}{f_{\text{ref}}} \right)^{\beta_1}, & f_X < f_b, \\ K' \left( \frac{f_X}{f_{\text{ref}}} \right)^{\beta_2}, & f_X \geq f_b, \end{cases}$$

where the normalization constants $K$ and $K'$ follow the relation

$$K' = K \left( \frac{f_{\text{ref}}}{f_b} \right)^{\beta_1 - \beta_2}, \quad f_b = \text{the X-ray flux of the break of the double power law, } f_{\text{ref}} = 10^{-14} \text{ erg s}^{-1} \text{ cm}^{-2}$$

is the normalization flux and $\beta_1$, $\beta_2$ are the power-law indices for fluxes fainter and brighter than the break flux, respectively. The cumulative counts follow the relation

$$N(> f_X) = \begin{cases} K \frac{f_{\text{ref}}}{f_{\text{ref}}^{\beta_1}} \left( \frac{f_X}{f_{\text{ref}}} \right)^{1+\beta_1} - \left( \frac{f_X}{f_{\text{ref}}} \right)^{1+\beta_1}, & f_X < f_b, \\ K' \frac{f_{\text{ref}}}{f_{\text{ref}}^{\beta_2}} \left( \frac{f_X}{f_{\text{ref}}} \right)^{1+\beta_2}, & f_X \geq f_b. \end{cases}$$

For the simulations, we adopt the best-fitting parameters determined by Kim (2007a) for the 2–8 keV counts: $\beta_1 = -1.58$, $\beta_1 = -2.59$ and $f_{\text{ref}}(2–10 \text{ keV}) = 2 \times 10^{-14} \text{ erg s}^{-1} \text{ cm}^{-2}$. The break flux determined by Kim (2007a) in the 2–8 keV band is shifted to the 2–10 keV energy range assuming $\Gamma = 1.4$. The normalization is fixed so that there are 7000 sources per deg$^2$ brighter than $f_X(2–10 \text{ keV}) = 10^{-16} \text{ erg s}^{-1} \text{ cm}^{-2}$, i.e. similar to the observed density of X-ray sources.

We adopt an X-ray spectrum with $\Gamma = 1.4$ and a total exposure time of 200 ks. Simulated ACIS-I event files are constructed by randomly placing within the Chandra field of view point sources with fluxes in the range $f_X(2–10 \text{ keV}) = 5 \times 10^{-17} – 10^{-12} \text{ erg s}^{-1} \text{ cm}^{-2}$. MARX does not simulate the Chandra background. This is added to the simulated images using the quiescent background event files produced by the ACIS calibration team using blank sky observations. In the following sections, it is demonstrated that using the proposed method for quantifying the sensitivity of X-ray imaging observations we can successfully recover the input source count distribution.

4 SENSITIVITY MAP CONSTRUCTION

The sensitivity map is an estimate of the probability that a source with flux $f_X$ in a certain energy band will be detected across the detector. This probability depends on the detector characteristics, the adopted observational strategy and the specifics of the source detection. Instead of extensive simulations, one can use statistics to approximate the source detection process, as this is essentially a Poisson experiment. Any source extraction method estimates the Poisson probability that the observed counts in a detection cell arise from random fluctuations of the background. The important
parameters in this exercise are the size and shape of the detection cell, which are well defined in our source detection method, and the Poisson probability threshold, $P_{\text{thresh}}$, below which an excess of counts is considered a source. By fixing $P_{\text{thresh}}$, one sets the minimum number of photons in a cell, $L$, for a formal detection.

The observed counts in a detection cell have a background and possibly a source component. Either of them can fluctuate so that their sum is higher than $L$. This either produces a spurious source in the case of a background fluctuation or can make a faint source appear with a brighter observed flux, i.e. the Eddington bias. Both these effects are part of the source selection process and should be accounted for by the sensitivity map.

The first step to construct such an image is to estimate the source-free background across the detector. This has an instrumental and a cosmic component, with the latter coming from sources below the sensitivity of the observation or photons in the extended wings of the PSF of detected sources. The background map is estimated using custom routines to first remove the counts in the vicinity of detected sources using an aperture size that is 1.5 times larger than the 90 per cent EEF radius. Pixel values in the source regions are replaced by sampling from the distribution of pixel values in local background regions. These are defined by annuli centred on each source with inner apertures equal to 1.5 times the 90 per cent EEF radius and widths of 50 arcsec. The resulting maps can then be used to estimate the mean expected background counts within any detection cell, $B$.

The cumulative probability that the observed counts in a particular detection cell will exceed $L$ is

$$P_S(\geq L) = \gamma(L, B),$$

where the function $\gamma(a, x)$ is defined as

$$\gamma(a, x) = \frac{1}{\Gamma(a)} \int_0^x e^{-t} t^{a-1} \, dt.$$

Adopting a detection threshold $P_{\text{thresh}}$, one can invert equation (3) numerically to estimate the (integer) detection limit $L$ for a cell with mean expected background $B$. Repeating this exercise for different cells across the image, one can determine $L$ as a function of position $(x, y)$ on the detector. This 2D image of $L$ values is the sensitivity map. Note that the sensitivity map is independent of the spectral shape of the source. A useful 1D representation of this image, with a wide range of applications, is the total detector area in which a source with flux $f_X$ can be detected. The cumulative distribution of the area plotted as a function of $f_X$ is often referred to as a sensitivity curve. This is constructed as follows. For a source with flux $f_X$ and a given spectral shape ($\Gamma = 1.4$ in this paper), we can determine the probability of detection in a cell with mean background $B$ and detection limit $L$. The total observed counts in the cell are $T = B + S$, where $S$ is the mean expected source contribution. In practise, this depends on the observation exposure time, the vignetting of the field at the position of the cell, embodied in the exposure map, and the fraction of the total source counts in the cell because of the PSF size.

$$S = f_X \times t_{\text{exp}} \times C \times \eta,$$

where $t_{\text{exp}}$ is the exposure time at a particular position after accounting for instrumental effects, $C$ is the conversion factor from flux to count rate for the adopted source spectral shape and $\eta$ is the EEF at the particular position. Both $B$ and $S$ fluctuate and therefore using equation (3) the probability that their sum exceeds the detection threshold is $P_{T; f_X}(\geq L) = \gamma(L, T)$. Fig. 1 plots $P_{T; f_X}(\geq L)$ against $f_X$ for a particular choice of $B$ and $L$ values, typical of a detection cell close to the aimpoint of a 200 ks Chandra observation in the 2–10 keV energy band. At faint fluxes, $S \rightarrow 0$ and

![Figure 1](image_url)
The mean expected total counts in the detection cell are \( T = S + B \), where \( S \) is determined as a function of flux from equation (5) and \( B \) is the local background value, then the probability of finding the observed number of total counts \( N \) (source and background) is

\[
P(f_X, N) = \frac{T^N e^{-T}}{N!} f_X^\beta,
\]

(6)

where the last term, \( f_X^\beta \), is for the Eddington bias and assumes that the differential X-ray source counts follow a power law of the form \( dN/df_X \propto f_X^\beta \). Equation (6) is graphically shown in Fig. 3 in the case of a particular source drawn from the simulations described in Section 3. The X-ray number counts are determined by simply dividing the sum of the probability distributions of individual sources, \( P(f_X, N) \), with the sensitivity curve determined in the previous section. This approach has the advantage that it accounts for source and background fluctuations, the Eddington bias and spurious detections in the catalogue.

Determination of \( P(f_X, N) \) for individual sources requires, however, knowledge of the source count power-law index \( \beta \). This is estimated by applying maximum likelihood (ML) methods to the unbinned data. The probability of the source \( i \) with total number of counts \( N_i \) in the surveyed area is

\[
P_i = \frac{\int P(f_X, N_i)df_X}{\int dN/df_X A(f_X)df_X}.
\]

(7)

The likelihood of a particular set of data is estimated by multiplying the probabilities \( P_i \) of individual sources. We can then estimate the power-law index \( \beta \) that maximizes the likelihood. It is straightforward to generalize the form for \( P_i \) in the case of a source count distribution that follows the double power law of equation (1).

We demonstrate this technique using the simulations described in Section 3. The source detection code described in Section 2 and the sensitivity map construction method of the previous section are applied to a total of 10 mock Chandra fields. We recover the input source count distribution in the 2–10 keV band by combining the 10 individual simulated source lists. Using the ML method, we estimate the bright and faint-end power-law indices as well as the break flux, \( \beta_1 = -1.62_{-0.06}^{+0.08} \), \( \beta_2 = -2.73_{-0.37}^{+0.30} \) and \( f_b = (2.0 \pm 0.6) \times 10^{-14} \text{ erg s}^{-1} \text{ cm}^{-2} \), in good agreement with the input values listed in Section 3.

6 APPLICATION TO REAL DATA

We apply the methods developed in the previous sections to deal with Chandra data to determine the differential source counts in the four standard X-ray spectral bands, soft (0.5–2 keV), hard (2–10 keV), ultra-hard (5–10 keV) and total (0.5–10 keV). We combine observations from six Chandra surveys, both deep pencil-beam and shallow wide-area. Table 1 presents information on these surveys, which include the Chandra Deep Field-North and -South (CDF-N/S), the Extended Chandra Deep Field South (ECDFS), the Extended Groth Strip (EGS), the ELAIS-N1 (EN1) and the XBOOTES survey. The combined sample has a total of 6295 unique sources, detected in different spectral bands, over a total area of 11.8 deg$^2$. This is the largest sample to date used for the determination of the X-ray number counts and can only be compared with the recent work of Kim (2007a) who combined observations from the ChaMP survey (Kim 2007b) with the Chandra Deep Fields.

The data from these surveys were reduced and analysed in the same way following methods described by Nandra et al. (2005b) and...
Laird et al. (2008). Briefly, standard reduction steps are followed using the CIAO version 3.2 data analysis software. Observations corresponding to the same pointing are merged into a single event file. The ECDFS, EGS, EN1 and XBOOTES surveys include multiple pointings, four, eight, 30 and 126, respectively. The CDF-S and the ECDFS observations although largely overlapping are treated as separate surveys. This is to avoid problems arising from merging regions with significantly different PSFs. Images are constructed in four energy bands 0.5–7.0, 0.5–2.0, 2.0–7.0 and 4.0–7.0 keV.

The X-ray catalogue for each spectral band is constructed using the source detection method of Section 2 adopting a Poisson detection probability threshold of 4 × 10⁻⁶. The total number of unique sources in each survey is shown in Table 1. In the case of duplicate sources in the overlap regions of adjacent pointings in the EGS, ECDFS and EN1 surveys, we keep the detection with the smallest off-axis angle. Also, for the ECDFS we exclude sources that overlap with the deeper CDF-S survey. The count rates in the 0.5–7.0, 0.5–2.0, 2.0–7.0 and 4.0–7.0 keV bands are converted to fluxes in the standard total, soft, hard and ultra-hard bands assuming a power-law X-ray spectrum with index $\Gamma = 1.4$ and Galactic absorption appropriate for each field. We note that this assumption ignores the hardening of the X-ray spectra with decreasing flux (e.g. Mainieri et al. 2002) or the different spectral properties of different X-ray source populations (e.g. AGN versus normal galaxies).

We apply the methods of Section 4 to estimate the sensitivity curves of the surveys listed in Table 1 taking into account overlapping regions (e.g. ECDFS and CDF-S). These are presented in Fig. 4 for the hard spectral band, 2–10 keV. We follow the prescription of Section 5 to construct and to fit the differential counts using the double power-law equation (1). The ML parameters for the four standard spectral bands are listed in Table 2. The results for the differential (normalized to the Euclidean slope) and cumulative number counts are plotted in Figs 5 and 6. The error bars in these figures are estimated using 100 bootstrap resamples of the data. We note that systematic uncertainties associated with the use of a fixed $\Gamma$ for the flux estimation or the EEF corrections are not taken into account in the calculation of errors. With decreasing flux, the area of the survey sensitive to sources of that flux becomes smaller. As a result, below a certain limit the observation does not provide a reliable census of the X-ray source population. We choose to plot the number counts to the flux limit corresponding to 1 per cent of the total surveyed area. This cut-off applies only to the graphical representation of the number counts and does not affect the ML calculation, where the decreasing survey area with decreasing flux is fully accounted for in the calculation. The adopted cut-off is typically 1.5–2 times fainter than the standard flux limit of a particular observation (see Fig. 2). As a result, the number counts derived here extend to fluxes that are 1.5–2 times fainter than previous determinations. This is demonstrated in Fig. 5 for the 0.5–2 and 2–10 keV bands, for which accurate estimates of the differential counts are available in the literature. Our work also has the advantage that all the fields used to determine the number counts have been analysed in a homogeneous way and that all the detected sources, even those close to the flux limit of the surveys in Table 1, have been used in the calculation. This is because our approach for determining the log $N$ – log $S$ correctly accounts for the completeness and flux bias corrections, particularly for sources with few photons close to the detection limit of a given survey.

Table 1. Stacking results.

<table>
<thead>
<tr>
<th>Survey</th>
<th>Obs. IDs</th>
<th>Exposure (ks)</th>
<th>Area ($\text{deg}^2$)</th>
<th>Sources</th>
</tr>
</thead>
<tbody>
<tr>
<td>CDF-N</td>
<td>580, 957, 966, 967, 1671, 2232, 2233, 2234, 2344, 2386, 2421, 2423, 3293, 3294, 3388-3391, 3408, 3409</td>
<td>2000</td>
<td>0.11</td>
<td>516</td>
</tr>
<tr>
<td>CDF-S</td>
<td>581 441 582 1672 2405 2239 2312 2313 2406 2409 1431</td>
<td>900</td>
<td>0.06</td>
<td>270</td>
</tr>
<tr>
<td>ECDFS</td>
<td>5015-5022, 6164</td>
<td>250</td>
<td>0.25</td>
<td>592</td>
</tr>
<tr>
<td>EGS</td>
<td>3305, 4357, 4365, 5841-5854, 6210-6223, 6366, 6391, 7169 7180, 7181, 7187, 7188, 7236, 7237, 7238, 7239</td>
<td>200</td>
<td>0.63</td>
<td>1325</td>
</tr>
<tr>
<td>EN1</td>
<td>5855-5884</td>
<td>5</td>
<td>1.47</td>
<td>545</td>
</tr>
<tr>
<td>XBOOTES</td>
<td>3596-3660, 4218-4272, 4277-4282</td>
<td>5</td>
<td>9.24</td>
<td>3056</td>
</tr>
</tbody>
</table>

The columns are as follows. (1) Survey name; (2) Chandra observation IDs used for each survey; (3) exposure time in ks. In the case of multiple pointings, this is the mean exposure time; (4) total surveyed area in deg². For the ECDFS, this includes the overlap with the CDF-S; (5) total number of sources in each survey. The ECDFS sources include those overlapping with the CDF-S.

Figure 4. Sensitivity curve in the hard band (2–10 keV) for the different Chandra surveys used to determine the differential X-ray source counts. XBOOTES: continuous line with the crosses; ELAIS-N1: continuous line marked with squares; EGS: the continuous line marked with triangles; ECDF-S: dotted line; CDF-S: short-dashed line and CDF-N: long-dashed line. The (red) dash–dotted line is the sum of the individual curves. The different slopes between the shallow and the deep surveys are the result of the outer regions becoming background limited.
Table 2. X-ray number count best-fitting parameters for the differential counts adopting the double power of equation (1). The cumulative counts \(N(>f_X)\) are obtained using equation (2).

<table>
<thead>
<tr>
<th>Band</th>
<th>Sources</th>
<th>(\beta_1)</th>
<th>(\beta_2)</th>
<th>(\log f_b)</th>
<th>(K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soft</td>
<td>4756</td>
<td>-1.58±0.02</td>
<td>-2.50±0.05</td>
<td>-0.04±0.06</td>
<td>1.51±0.03</td>
</tr>
<tr>
<td>Hard</td>
<td>2565</td>
<td>-1.56±0.04</td>
<td>-2.52±0.07</td>
<td>+0.09±0.08</td>
<td>3.79±0.08</td>
</tr>
<tr>
<td>Ultra-hard</td>
<td>1081</td>
<td>-1.70±0.08</td>
<td>-2.57±0.07</td>
<td>-0.09±0.06</td>
<td>2.36±0.08</td>
</tr>
<tr>
<td>Total</td>
<td>5561</td>
<td>-1.58±0.02</td>
<td>-2.48±0.03</td>
<td>+0.42±0.07</td>
<td>3.74±0.05</td>
</tr>
</tbody>
</table>

The columns are as follows. (1) Spectral band; (2) number of sources above the \(4\times10^{-6}\) detection threshold in a given energy band; (3) faint end index of the double power law; (4) bright end index of the double power law; (5) log of the break flux in units of \(10^{-14}\) erg cm\(^{-2}\) s\(^{-1}\). (6) Normalization in units \(10^{16}\) deg\(^{-2}\)/(erg cm\(^{-2}\)s\(^{-1}\)).

The best-fitting parameters for the 0.5–2, 2–10 and 0.5–10 keV bands in Table 1 are in good agreement with recent estimates by Kim (2007a), who also combined deep pencil-beam surveys with shallow observations over a wide area with Chandra to determine the number counts in the 0.5–2, 2–8 and 0.5–8 keV bands. Also presented here for the first time is the \(\log N - \log S\) in the 5–10 keV band over 4 dex in flux. This wide flux range allows the determination of the flux of the break in the double power-law representation of the 5–10 keV number counts.

In Fig. 5, the soft band source counts at fluxes fainter than about \(6\times10^{-17}\) erg s\(^{-1}\) cm\(^{-2}\) lie systematically above the best-fitting double power law. The emergence of a population of normal star-forming galaxies at faint fluxes can explain this excess. This is demonstrated in Fig. 7 plotting the expected star-forming galaxy number counts, estimated by integrating the X-ray luminosity function of these systems at low redshift (Georgakakis et al. 2006) assuming pure luminosity evolution of the form \(\propto (1+z)^{3.4}\) (e.g. Georgakakis et al. 2007).

Contrary to the soft-band, the 2–10 and 5–10 keV counts at faint fluxes in Fig. 5 show tentative evidence, significant at \(\approx 2\sigma\) level, for a flattening of the faint-end slope at the limit of the deepest X-ray survey of the sample, the CDF-N. Kim (2007a) has shown that the \(\log N - \log S\) distribution of sources depends on their hardness ratio (HR). Sources with HR > 0 have steep differential counts that do not show evidence for a break in the slope at the flux limit of the ChaMP survey. In contrast, sources with HR < 0 show the characteristic break in their number count distribution. It is suggested that sources with HR > 0 lie, on average, at redshifts...
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Figure 6. Cumulative number counts in the soft, total, hard and ultra-hard bands for the combined Chandra surveys listed in Table 1. The continuous black line is the estimated number counts and the dashed lines correspond to the 1σ rms uncertainty estimated using bootstrap resampling of the data. For clarity, the ML fits to the data are not shown. The 1 Ms CDF-N fluctuation analysis results for the soft and hard bands (Miyaji & Griffiths 2002) are shown with the dotted line wedges.

lower than the population with HR < 0 and as a result they do not show the cosmological evolutionary effects that cause the break in the log N − log S (Harrison et al. 2003; Kim 2007a). The change in slope at the faint-end of the 2–10 and 5–10 keV counts is likely related to the relative contribution of sources with HR ≲ 0.

Fig. 8 plots the contribution of the point sources to the diffuse XRB in different spectral bands. This is estimated by integrating the double power-law relation using the best-fitting parameters listed in Table 2. For the level of XRB, we adopt the average flux densities of \((7.52 \pm 0.35) \times 10^{-12}\) erg s\(^{-1}\) cm\(^{-2}\) deg\(^{-2}\) for the 0.5–2 keV band from Moretti et al. (2003) and \((2.24 \pm 0.11) \times 10^{-11}\) erg s\(^{-1}\) cm\(^{-2}\) deg\(^{-2}\) for the 2–10 keV range from De Luca & Molendi (2004). For the total spectral band, 0.5–10 keV, we add the above values and estimate an XRB flux density of \((2.99 \pm 0.12) \times 10^{-11}\) erg s\(^{-1}\) cm\(^{-2}\) deg\(^{-2}\) for the 2–10 keV band from De Luca & Molendi (2004) to estimate \((1.23 \pm 0.06) \times 10^{-11}\) erg s\(^{-1}\) cm\(^{-2}\) deg\(^{-2}\). The fraction of the XRB resolved in point sources in different energy bands to the limits of the deepest survey in the sample are listed in Table 3. In addition to the statistical uncertainty listed in that table, there is a systematic error of about 10–20 per cent related to the uncertainty in the determination of the absolute normalization of the XRB (e.g. Revnivtsev et al. 2003, 2005). In Table 3, the 2–10 and 5–10 keV bands resolve similar fractions of the XRB, 74 ± 4 and 72 ± 4 per cent, respectively. This is consistent with the work of Worsley et al. (2005). In that study, the fraction of the XRB resolved into point sources is nearly constant at 2–6 keV and drops substantially at energies >6 keV to about 50 per cent in the 8–12 keV band.

The resolved XRB fractions in the 2–10 and 5–10 keV bands can be used to place constraints on the spectral shape of the unresolved XRB. First, the difference in the sensitivity in the two energy bands needs to be accounted for by matching their flux limits. The 5–10 keV flux limit of \(2 \times 10^{-16}\) erg s\(^{-1}\) cm\(^{-2}\) corresponds to \(f_X(2–10) = 3.6 \times 10^{-16}\) erg s\(^{-1}\) cm\(^{-2}\) for \(\Gamma = 1.4\), i.e. the mean spectrum of the XRB. At this flux, 70 ± 4 per cent of the XRB in the 2–10 keV band is resolved into point sources. We then assume that there is a single population that is responsible for the unresolved part of the XRB in both the 2–10 (30 ± 4 per cent) and 5–10 keV (28 ± 4 per cent) bands. There has been recently speculation on whether the unresolved background at hard energies is produced by Compton thick AGN (Worsley et al. 2005; Gilli et al. 2007). In order to test this possibility, we adopt for the X-ray spectral shape of this population the Compton reflection models of Magdziarz & Zdziarski (1995) as

Figure 7. Soft-band differential source counts in comparison with the $dN/df_X$ for star-forming galaxies (Georgakakis et al. 2007). The surface density of these sources can account for the excess counts above the broken double power-law expectation at fluxes below about $6 \times 10^{-17}$ erg s$^{-1}$ cm$^{-2}$.

Figure 8. Integrated intensity and contribution to the diffuse XRB of the point sources detected in different spectral bands. The (red) curves are estimated from the ML fits to the differential number counts. The level of the XRB is shown with the horizontal continuous line. The dashed lines correspond to the statistical 1σ rms uncertainty to this value.

Table 3. Resolved XRB fractions.

<table>
<thead>
<tr>
<th>Band</th>
<th>Limit</th>
<th>Fraction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soft</td>
<td>$1 \times 10^{-17}$</td>
<td>82 ± 4</td>
</tr>
<tr>
<td>Hard</td>
<td>$1 \times 10^{-16}$</td>
<td>74 ± 4</td>
</tr>
<tr>
<td>Ultra-hard</td>
<td>$2 \times 10^{-16}$</td>
<td>72 ± 4</td>
</tr>
<tr>
<td>Full</td>
<td>$7 \times 10^{-17}$</td>
<td>81 ± 3</td>
</tr>
</tbody>
</table>

The columns are as follows. (1) X-ray energy band; (2) flux limit in the corresponding spectral band that the resolved XRB fraction is estimated. The units are in erg s$^{-1}$ cm$^{-2}$. At these flux limits, the area curve of the deepest survey in the sample, the CDF-N, drops to about 1 per cent of its maximum value; (3) per cent fraction of the XRB resolved into point sources.

implemented in the PEXRAV spectral energy distribution of XSPEC. We assume a mean redshift $z \approx 1$, a solid angle of $2\pi$, solar abundance for all elements and an average inclination relative to the line of sight $\cos i = 0.45$. Only the reflection component was used, i.e no direct radiation. We find that if the entire 30 per cent of the unresolved background in the 2–10 keV band [to the limit $f_X(2–10) = 3.6 \times 10^{-16}$ erg s$^{-1}$ cm$^{-2}$] is produced by such sources, then their contribution to 5–10 keV XRB is 39 per cent, which exceeds
the unresolved fraction (28 ± 4 per cent) at the 2.8σ level. Moving the mean redshift of the Compton thick AGN population to \( z \approx 2 \) reduces the significance of the excess to 2.2σ. We conclude that either some of the sources in the 5–10 keV selected sample lie below the flux limit \( f_X(2–10) = 3.6 \times 10^{-16} \text{erg s}^{-1} \text{cm}^{-2} \) or the unresolved XRB fraction in the 2–10 keV band cannot be entirely due to a single population of Compton thick AGN.

7 CONCLUSIONS

A new method is presented for determining the sensitivity of X-ray imaging observations, which accurately estimates the probability of detecting a source with a given X-ray flux accounting for observational effects, such as vignetting, flux estimation biases and the fraction of spurious sources expected in any source catalogue. A major advantage of the proposed method is that it is analytical and therefore does not require a large number of cumbersome ray-tracing simulations to quantify the effects above. We demonstrate how to use the sensitivity maps determined by our new method in order to accurately estimate the number counts in different X-ray spectral bands, using all the detected sources, even those with few counts, for which the completeness and flux bias corrections are large. This method is applied to real Chandra data. The sample includes both deep pencil-beam and shallow wide-area surveys covering a total area of about 11.8 deg² and includes over 6000 unique sources. We present, for the first time, the X-ray counts in the 5–10 keV band over a wide range of X-ray fluxes (4 dex) and determine the break flux in this band. We also find evidence for an upturn in the 0.5–2 keV differential counts below about \( 6 \times 10^{-17} \text{erg s}^{-1} \text{cm}^{-2} \), which we attribute to the emergence of a population of star-forming galaxies at faint fluxes. Based on the fraction of the XRB resolved in the 2–10 and 5–10 keV bands, we argue that a single population of Compton thick AGN cannot by itself produce the entire unresolved X-ray background in the 2–10 keV energy range.

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REFERENCES


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