The 2XMM catalogue and variability of X-ray sources

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Abstract

We released the 2XMM catalogue, the largest ever X-ray source catalogue, on 22 August 2007. It contains 246,897 detections drawn from 3491 public XMM-*Newton* observations, which relate to 191,870 unique sources. The time variability, as well as spectrum, has been studied for the sources that have reasonable statistics, numbering 38,320 detections. Here we present the highlight of the 2XMM catalogue, in particular the time variability of the point sources, and discuss the potential future study with the X-ray monitoring instrument, MAXI.

Key words: X-ray: catalogue — source: variability — XMM-Newton

1. Introduction

Surveys are always important in astronomy in any wavelength. However it is neither easy nor often practical to perform deep and wide-field surveys, as the instruments with good spatial resolution and accordingly high sensitivity generally have a small field of view, whereas those with a wide field of view have only a poor sensitivity. In the light of this serendipitous surveys play an important role, which offers good sensitivity, as well as moderately wide and reasonably unbiased coverage.

In the X-ray band ROSAT All-Sky Survey (RASS) provides the best sample in terms of coverage (i.e., all-sky) and reasonable depth for sensitivity (Voges et al. 1999, 2000). However the energy band is limited to below ~2 keV. In the harder energy band above 2 keV, HEAO-1 all-sky survey is still the best in terms of coverage, although the sensitivity is poor. Various results have been published to compensate this lack of sensitivity in the hard X-ray band with serendipitous surveys, of which ASCA-AMSS (Ueda et al. 2005) is probably the most notable to date.

The XMM-Newton observatory is equipped with CCD cameras (EPIC), which has the large field of view, combined with the good sensitivity, good spatial resolution and large effective area of its mirrors. Hence it provides an ideal opportunity for the serendipitous survey. Even though most of the target fields were selected in a naturally biased way to observe their primary targets, the areas surrounding the targets are expected to give a reasonably unbiased dataset for the survey.

We have performed the serendipitous survey using all[*1] the public data of XMM-Newton prior to 1 May 2007 as the key project of the XMM-Newton Survey Science Centre (SSC), and released the result as the 2XMM catalogue on 22 August 2007. It contains 246,897 detections, and among those 191,870 sources are regarded as unique. This is the largest ever X-ray source catalogue.

The full detail of the catalogue is found in Watson et al. (2008). In this paper we describe the highlights of the catalogue result, as well as some time variability characteristics of the catalogued sources, and further discuss its use in the future all-sky X-ray monitoring programme, particularly the MAXI.

2. The 2XMM catalogue – overview

2.1. The observed area and sensitivity

The EPIC onboard XMM-Newton has a good and direct imaging capability with the size of the point-spread function of ~10 arcsec, with the field of view (of the combined three EPIC instruments) of ~30 arcmin in diameter, with the large effective area of 2000 cm^2 at 1 keV for the sensitive energy band of 0.2–12 keV. The 3491 observed fields observed in 7 years, as is shown in Fig. 1, in total covers ~370 deg^2, i.e., ~1 per cent of the sky.

Fig. 2 shows a couple of examples of field of views of EPIC, which were used to compile the 2XMM catalogue. Even though not all the fields are in the ideal state, we

[*1] Some fields with bad quality or observed in an unsuitable mode for the serendipitous survey study were excluded (see Watson et al. 2008 for detail).

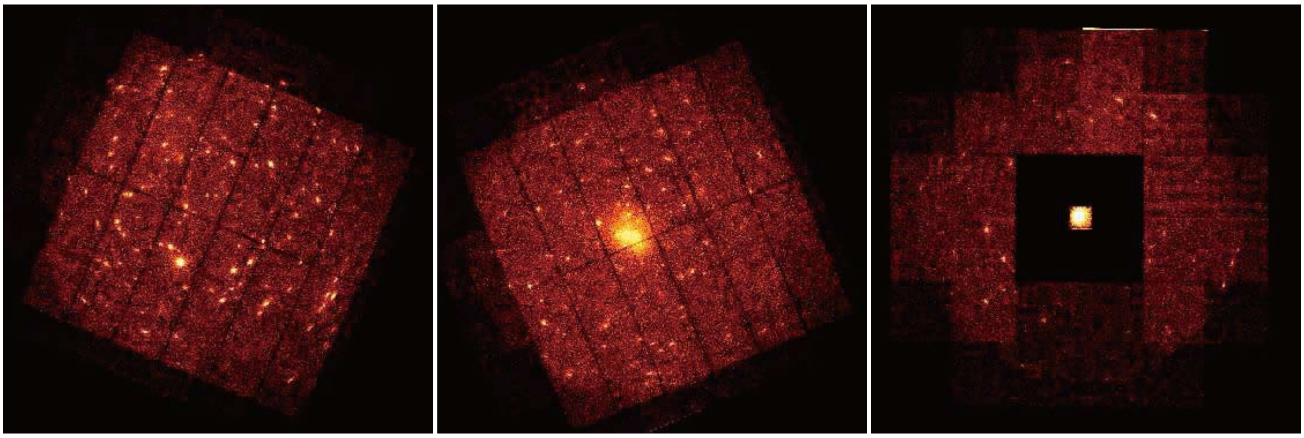

Fig. 2. Example field of views used in the 2XMM catalogue. *Left panel*: a deep observation in a high-galactic-latitude field, *Middle panel*: a distant cluster of galaxy, *Right panel*: an observation with a different mode from the most standard one — we did not use the central CCD chip in this case, whereas we did process and use the peripheral CCD chips.

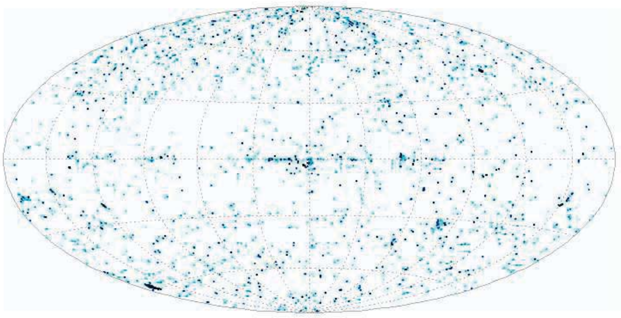

Fig. 1. Hammer-Aitoff equal area projection in the galactic coordinates of the fields used in the 2XMM catalogue.

have achieved reasonably clean data set by selecting the area used for the source detection, as well as further manual screening (Watson et al. 2008).

The sensitivity varies by more than an order of magnitude, depending on the exposure and coverage of the three EPIC instruments of each area of interest, from observation to observation. The limiting flux for the pn camera, which is the most sensitive one among all three EPIC instruments, are $[1, 9, 25] \times 10^{-14}\,\mathrm{erg\,cm^{-2}\,s^{-1}}$ for >90 per cent sky coverage in the soft (0.5–2 keV), hard (2–12 keV) and hardest (4.5–12 keV) bands, respectively.

2.2. The catalogued sources

The 2XMM catalogue contains $246,897$ detections, of which $191,870$ sources are regarded as unique. Of these, $27,522$ sources were observed more than once. Of these unique sources, ~ 1400 sources are plausibly associated with the intended target. This means that $< 1\%$ of 2XMM sources are the target of the observation. We should note however that the number of sources *associated* with the target can be much larger in a few observations, such as nearby galaxies.

The catalogue contains various parameters, such as hardness ratio, including the source matching with the external databases (Watson et al. 2008). We have also extracted and released the plots of time-series and spectra for the sources that have enough statistics.

The 2XMM catalogue contains the entry of the spatial extent of each source, and indicates that $20,837$ detections out of $246,897$ are suggested to be extended. However due to much more degree of freedom in the case of extended sources in comparison with point-like sources, this figure should not be taken straightforwardly. Indeed the *flag* entry in the catalogue shows that roughly a half of these detections of extended sources are suspicious. Nevertheless a further close look revealed that the rate of spurious detections of extended sources seems to be reasonably low (<5 per cent), if the clean detections (as stated in flagging) with reasonably high detection significance are chosen (Watson et al. 2008).

The 2XMM catalogue contains detections down to an EPIC detection likelihood L of 6. Around 90% of the detections have $L > 8$ and $\sim 82\%$ have $L > 10$. We have performed the Monte-Carlo simulation to investigate the false detection rate (Fig. 3). We found that the rates of the false detection for point sources in quiet high-galactic-latitude fields are roughly $\sim [2, 1, 0.5]$ per cent for the chosen minimum likelihood of $L_{\mathrm{min}} \geq [6, 8, 10]$, respectively, and that these rates are approximately constant over the range of exposures of each observation. The further detail is discussed in Watson et al. (2008).

The 2XMM catalogue lists the statistical positional error for each detection and each unique source. In addition we estimated the systematic positional error to be $\sigma_{\mathrm{sys}} = 0.35$ arcsec, based on the study of our data compared with the Sloan Digital Sky Survey (SDSS) DR5 Quasar Catalog (Schneider et al. 2007). The typical value for the statistical error is ~ 0.6 arcsec. Therefore

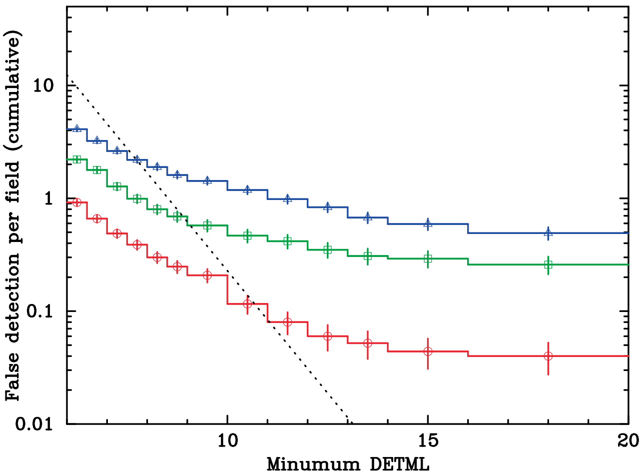

Fig. 3. The number of false detections per field estimated via simulations for typical high Galactic latitude fields as a function of the minimum likelihood $L_{\rm min}$ for various exposure times. The red circles show the results for exposures of $\sim$ 70% of the median values, whereas the green squares and blue triangles show those with the exposures of 3 and 10 times higher than that (red ones), respectively. The dotted line represents the theoretical false detection number. This figure is adopted from Fig. 10 in Watson et al. (2008).

the total positional uncertainty is $\sim$ 0.7 arcsec. Although there is a significant tail for the higher end in the statistical error, the majority of the sources have the total positional uncertainty of $\lesssim 2$ arcsec.

2.3. Flux distribution and Log$N$-Log$S$

Fig. 4 demonstrates the flux distribution of point sources in the 2XMM catalogue, where the sources with suspicious detection are excluded. The majority of the sources have the 2–12 keV flux of the order of 10^{-14} erg cm^{-2} s^{-1}, whereas there are a significant number of sources with the flux above 10^{-12} erg cm^{-2} s^{-1}.

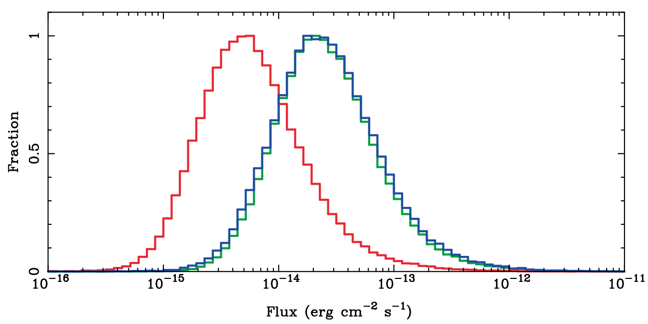

Fig. 4. The flux distribution of point sources in the 2XMM catalogue for the soft (0.5–2 keV; red), hard (2–12 keV; blue) and total (0.5–12 keV; green) bands. The sources with any suspected flag or detection likelihood of less than 10, or that are the targets of each observation, are excluded from this plot. This figure is adopted from Watson et al. (2008).

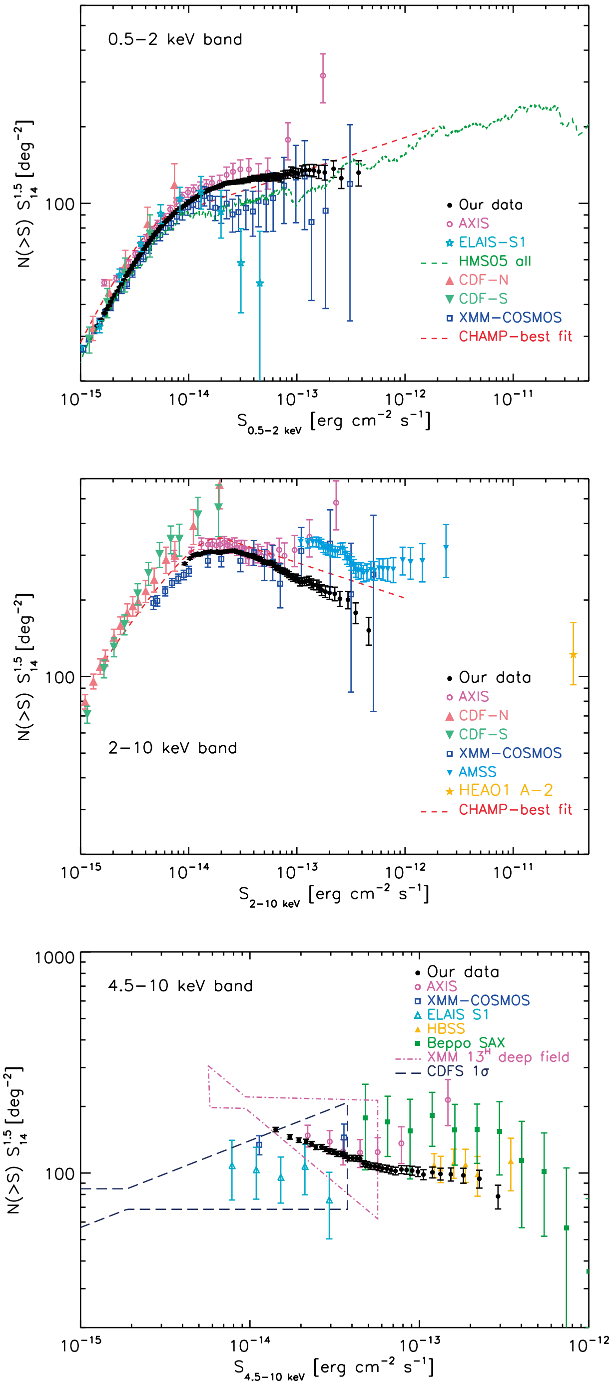

Fig. 5. The Log$N$-Log$S$ relation of the 2XMM sources (black) from the 1129 selected observations of high-latitude quiet fields, together with the results from other X-ray surveys (other colours). They are normalised to the standard Euclidean space for the energy band of 0.5–2, 2–10 keV and 4.5–10 keV for *Top*, *Middle* and *Bottom* panels, respectively. The error bars correspond to 1σ confidence. These figures are adopted from Mateos et al. (2008).

Fig. 4 includes the sources from both low and high galactic latitudes. As a result some of them should have significant galactic absorption in the line of sight, which adds an undesirable complication for scientific study. Thus we have selected the high-galactic-latitude ($|b_{\rm II}| > 20°$) and quiet field of views, which covers the sky area of 132.3 $\deg^2$, and constructed Log$N$-Log$S$ relation plot for the sources in those fields (Fig. 5).

The selected field of views span the entire galactic longitude reasonably evenly in both galactic northern and southern hemispheres. Therefore the dataset should be least affected with the possible cosmic variance. On the other hand the sensitivity is obviously not as good as other modern deep X-ray surveys for fainter sources.

In the soft energy band of below 2 keV, our result confirms the previous ones in other X-ray surveys with better statistics for the medium flux range (10^{-15} – 10^{-12} erg cm^{-2} s^{-1}). In the hard energy band above 2 keV, our result basically confirms the previous ones in better statistics, except for some difference in the flux range of 10^{-13} – 10^{-12} erg cm^{-2} s^{-1}. In the hardest energy band of 4.5–10 keV, where XMM-Newton has the most distinctively higher sensitivity in comparison with other X-ray satellites, our result gives by far the tightest constraints to the Log$N$-Log$S$ relation in the flux range of 10^{-14} – 3×10^{-12} erg cm^{-2} s^{-1}. Comparison with the popular synthesis models suggests that the models may overpredict the number of faint absorbed AGNs (see Mateos et al. 2008 for detailed discussion).

2.4. Availability

The full 2XMM catalogue contains 297 columns (Watson et al. 2008) for each detection. The primary site for it is our XMM-SSC webpage:
http://xmmssc-www.star.le.ac.uk/Catalogue/ . It provides the full documentation and the hyper-links to the other hosting sites, such as XCAT and GSFC.

Associated with the catalogue table, an extensive range of data products such as the EPIC images from each observation and the spectra and time-series data when available, namely when a detection has enough statistics, are provided from the following websites:

ESA/XSA
http://xmm.esac.esa.int/xsa/

LEDAS
http://www.ledas.ac.uk/xmm/2xmmlink.html

The latter also supplies a single HTML summary page for each detection, which gives the key parameters including those for the corresponding unique source, as well as the hyper-links to the external databases.

2.5. Ongoing works of the XMM catalogues

We, the SSC, are processing further available public observations since the release of the 2XMM catalogue. It is expected that roughly ~35,000 sources per year will be detected in XMM-Newton observations.

We are in the final stage of compiling the incremental 2XMM catalogue (2XMMi) that contains the detections from roughly one-year worth new observations in addition to all the detections in the 2XMM catalogue. The 2XMMi catalogue includes 289,083 detections, namely the increase by ~42,000 detections since the 2XMM catalogue. It will be released in the end of August 2008.

We are also developing the publicly available facility to estimate the upper limit of the XMM-Newton X-ray flux for any given celestial position, when the source was not detected in the observations included in the 2XMM catalogue. The gateway will be set up in the SSC website (see Sec. 2.4.) soon.

3. Time variability of the 2XMM sources

In each observation, we have produced the time-series of each detected source when they have enough count statistics, subtracted the suitable background, and the performed the χ^2-test against the null hypothesis of constancy. We found that ~10 and ~5 per cent of the sources among tested for the respective fluxes of $\geq 10^{-11}$ and $\geq 10^{-12}$ erg cm^{-2} s^{-1} are variable during its observation, of which the typical exposure time is 4 hours. This difference in the rate of variable sources is likely to be due to the statistics of the sources, rather than the nature of the sources itself. There is no indication for any significant trend between the source variability, (spectral) hardness and source position in the galactic latitude.

The identification of these variable sources with the Simbad database reveals that ~40 per cent of those are identified as non-degenerate stars, ~13 per cent as either X-ray binaries (including cataclysmic variables) or AGNs, and ~45 per cent as unidentified in the Simbad database. The completeness of the Simbad database for different object types is known to be highly non-uniform. Hence this can not be the definitive study. However it implies that even non-degenerate stars can be substantially variable.

Among the point-like 2XMM sources with the flux of $> 5 \times 10^{-14}$erg cm^{-2} s^{-1} with good enough statistics and clean detection flag, ~4700 sources have been observed and detected in more than one occasion. We found that 42 per cent of those ~4700 sources shows the significant variability between observations. In particular 99 per cent of the sources that show the short-term (within a single observation) variability are found to show the long-term (spanning multi-observations) variability as well.

4. Use of the 2XMM catalogue with the MAXI

The MAXI will monitor almost the entire sky every 90 minutes with the unprecedented sensitivity as the all-sky X-ray monitor (e.g., Matsuoka in this proceeding). Therefore it is expected to see a number of sources, particularly transient sources, that have never been detected before.

However due to its poor spatial resolution of the MAXI, it will be sometimes not a trivial task to resolve sources in congested fields, such as the Galactic plane. If the region has ever been observed with XMM-Newton, the 2XMM catalogue will be a useful template to estimate the contribution from weak sources with the MAXI field of view, the flux of each of which may be below the detection threshold of the MAXI scan.

In case of the detection of new transient sources, the study of the X-ray counterpart (with much greater precision for the position), its nature in quiescence and its possible past recurrent activity are possible with the use of the 2XMM catalogue, providing the source is in the field of views included in the 2XMM catalogue. The 2XMM catalogue also provides the information of the possible counterpart in other wavelengths.

Another definite possibility is the statistical study of the characteristics of the X-ray sources. The MAXI will provide the statistical nature of the X-ray sources, such as the flux and time-scale of the variability in the brighter side, whereas the 2XMM catalogue, being the largest X-ray source catalogue, offers that in the fainter side, as a good complementary work with the MAXI.

5. Summary

We have constructed and released the 2XMM catalogue, the largest ever X-ray source catalogue. It contains 246,897 detections with XMM-Newton, of which 191,870 sources are unique. The sources in the 2XMM catalogue were in principle serendipitously detected. Although the list of 191,870 unique sources include the targets of each observation, the fraction is less than 1 per cent.

$\gtrsim$90 per cent of these sources are point-like. The false detection rate for the point-like sources in a quiet high-galactic-latitude field is $\sim$2 per cent, while users of the 2XMM catalogue can easily apply more strict condition to filter suspicious detections based on the detection likelihood of each source provided in the catalogue.

The 2XMM catalogue gives much tighter constraints to the Log$N$-Log$S$ relation of the X-ray source distribution, which implies the need of some change or modification in the population synthesis models. It is not inconsistent with the previous observational results.

We have found time variability of all sorts of point sources spread across the entire sky. This confirms that the time variability is a very common nature for most, if not all, of the X-ray point sources.

The incremental XMM catalogue, the 2XMMi catalogue, will have been released by the time this paper is published.

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