The XMM-Newton EPIC Background and the production of Background Blank Sky Event Files *

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ABSTRACT

Aims. We describe in detail the nature of XMM-Newton EPIC background and its various complex components, summarising the new findings of the XMM-Newton EPIC background working group, and provide XMM-Newton background blank sky event files for use in the data analysis of diffuse and extended sources.

Methods. Blank sky event file data sets are produced from the stacking of data, taken from 189 observations resulting from the Second XMM-Newton Serendipitous Source Catalogue (2XMMp) reprocessing. The data underwent several filtering steps, using a revised and improved method over previous work, which we describe in detail.

Results. We investigate several properties of the final blank sky datasets. The user is directed to the location of the final data sets. There is a final data set for each EPIC instrument-filter-mode combination.

Key words. Surveys - X-rays: diffuse background - X-rays: general

1. Introduction

The XMM-Newton observatory (Jansen et al. (2001)), with the two EPIC MOS (Turner et al. (2001)) and one EPIC PN (Strüder et al. (2001)) cameras at the foci of the three telescopes, provides unrivalled capabilities for detecting low surface brightness emission features from extended and diffuse galactic and extragalactic sources, by virtue of the large field of view of the X-ray telescopes and the high throughput yielded by the heavily nested telescope mirrors. In order to exploit the excellent EPIC data from extended objects, the EPIC background (BG), now known to be higher than estimated pre-launch, needs to be understood thoroughly.

In 2005 a working group was set up to organise various investigations into the BG, to define the BG material useful for the general user and to place this BG material and findings of the group on the main XMM-Newton SOC web pages. This paper concentrates on one aspect of this work, namely that of the production of blank sky background event files, constructed for each of the EPIC instruments in each filter/mode combination.

The work described in this paper follows on from that of Read & Ponman (2003). The number of observations used in this analysis has increased from 72 to 189, greatly improving the signal-to-noise ratio. Further changes to the previous dataset have been the inclusion of thick filter observations in the analysis and other improvements described later.

All the background product files (event files, exposure maps, related software), together with other scripts and procedures for XMM-Newton background analysis are available from the official ESA site:

http://xmm.vilspa.esa.es/external/xmm_sw_cal/background/index.shtml.

The activities of the BG working group has led to a greater understanding of the complex components that make up the XMM-Newton EPIC BG. In section 2 of this paper we describe these various components, presenting a review of our current understanding of the BG. In section 3 we describe the production of the blank sky event files, detailing improvements made over previous work in the filtering stages using current knowledge of the BG. In section 4 we detail some properties of these files, and in section 5 we discuss the use of these files and present software that we have written and made available for use with the blank sky event files. Finally, in section 6 we

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present our conclusions and discuss future plans for analysing the BG.

2. The XMM-Newton EPIC X-ray Background

Given the complex nature of the EPIC background, and that new components of the background have recently been discovered by the BG working group and others, it is appropriate that a comprehensive description of the EPIC background should be given:

The EPIC background can be separated into particle, photon and electronic noise components (as described in the work of Lumb et al. (2002) and Read & Ponman (2003) and references therein). Several contributions are focused by the mirrors, whereas others arrive at the detectors directly through the shielding. The particle background can be further sub-divided into contributions from soft protons and cosmic-ray induced events, and the photon background can be sub-divided into contributions from hard and soft X-rays. In this section we describe each of these components, discussing their temporal, spectral and spatial properties. A table summarising the components of the background can be found via the official XMM-Newton pages.

2.1. Particle background

The particle background consists of focused soft protons and unfocused cosmic ray induced events.

2.1.1. Soft protons

This contribution to the background comes from solar soft protons, accelerated by magnetospheric reconnection events and trapped by the Earth’s magnetosphere, which are then gathered by XMM-Newton’s grazing mirrors. They dominate times of high background. These soft protons occur in flares up to 1000% of the quiescent level in an observation. They are highly unpredictable and affect 30% to 40% of XMM-Newton observation time. The frequency of soft protons seen increases closer to perigee. Within a single observation, a significant component may survive after good time interval screening (de Luca & Molendi 2004). Spectrally the soft protons are variable in intensity and shape. For energies > 0.5 keV the continuum spectrum, which shows no lines, can be fitted by an unfolded Xspec power law, i.e. one not convolved with the instrumental response (specifically a double-exponential or broken power law, with the break energy at approximately 3.2 keV, and with the spectrum becoming flatter at higher intensities). Below 0.5 keV, much less flux is seen (Kuntz et al. in preparation). The soft protons are distributed over the detector in a similar manner to X-rays, but the vignetting function is flatter than for photons. Also for the low-energy soft protons the vignetting function is flatter than that of high-energy protons. They are only observed inside the FOV (though during times of intense solar flares, which are unfocussed), the out-FOV signal can be greatly increased. There is no other spatial structure seen in the PN, but some structure may occur in the MOS due to the presence of the Reflection Grating Array on board XMM-Newton. An as yet poorly understood soft proton feature is seen in MOS CCD-2 at low energies (Kuntz et al. in prep.).

2.1.2. Internal cosmic ray induced events: the instrumental BG

This component of the BG results from high-energy particles producing charge directly in the CCDs, and from the interaction of high energy particles with the detector, causing associated instrumental fluorescence. Within an observation this component can vary by up to 10%. For the MOS cameras above 2 keV there is no change seen in the continuum and only small changes seen in the fluorescence lines, but below 1.5 keV the continuum varies, possibly due to the redistribution of the Al calibration line (de Luca & Molendi 2004). From observation to observation there is some variation; up to 10 times more intense an effect can be seen during periods of intense solar flares, but no increase is seen after the occurrence of solar flares so activation is unlikely.

The continuum spectrum is flat (with an index ~0.2). The instrumental fluorescence lines for MOS are found at 1.5 keV (Al-K), 1.7 keV (Si-K), plus some contribution from high energy lines (Cr, Mn, Fe-K and Au). For the PN, Al-K is seen at 1.5 keV, whereas the silicon line is self-absorbed, and high energy contributions are seen from Cu, Ni, Zn and K. Detector noise occurs below 0.3 keV.

The internal instrumental BG has a spatial distribution different from that of X-ray photons as it is not vignetted. In the outer CCDs and outside the field of view (FOV) for MOS there is more Al seen than Si, whereas the CCD edges show enhanced Si. There are continuum differences between the out-FOV and in-FOV below the Al-line, possibly resulting from redistribution. There is more Au seen out-FOV due to the Al-shielding which is coated with gold on its inner surfaces. Energies and widths of the lines are stable, whereas line intensities can vary. In the PN, line intensities show large spatial variation from the electronics board, for example the well-known ‘copper hole’, where a deficit in high-energy instrumental lines is seen at the detector centre (Freyberg et al. (2004)). Residual low-energy instrumental BG components are seen near the CAMEX readout areas.

2.2. Electronic noise

Electronic noise results from bright pixels and parts of columns, CAMEX readout noise in the PN and artificial low-energy enhancements in the outer CCDs of MOS. Dark current may also contribute, but this is thought negligible.

No temporal variations are seen within an observation apart from the bright pixel and column component that can vary by up to 10%. Bright pixels fluctuate greatly between observations. For the PN, the CAMEX readout noise is mode dependent; extended-full-frame mode suffering the least from this noise, and small window mode the most. Artificial low-energy enhancements may affect up to 20% or more of observations, and are enhanced during periods of high BG rate.
Spectrally, this component is seen at low energies (below 300 eV) for the bright pixel and CAMEX readout contributions. Artificial low-energy enhancements are sometimes observed below 500 eV in certain MOS CCDs (Kuntz et al. in prep., Pradas & Kerp (2005)).

This component is distributed differently from genuine X-ray photons and is not vignetted, apart from the artificial low-energy enhancements in the MOS cameras. The bright pixels and columns are seen at certain locations; structure is seen near to the PN readout (CAMEX). Certain MOS CCDs show some peculiarities in and out of FOV (Kuntz in prep.) and spatial inhomogeneities are seen within a particular MOS CCD.

2.3. Photon background

The photon background can be split into components from hard and soft X-rays and these components are focused by the mirrors.

2.3.1. Hard X-ray photons

The hard X-ray background photons mainly originate from unresolved AGN within the FOV. There are also single reflections into the FOV from all kinds of out-FOV sources, both bright and faint, resolved and unresolved (the unresolved out-FOV sources being, as for the in-FOV, predominantly AGN). Out-of-time events (OOT) are also a contributor to the hard X-ray BG of the PN.

The hard X-ray photon BG does not vary within an observation or between observations, although OOT events are mode dependent for the PN; the full-frame mode experiencing more of this effect than both the extended-full-frame and large window mode, due to the percentage of the frame time used for readout.

The hard X-ray photon BG can be modelled by a power law of spectral index ~1.4. In times of low-BG, and below 5 keV, this component dominates over the internal component of the BG, whereas above 5 keV, the internal component dominates. As they are genuine X-ray photons, they are spatially vignetted.

Diffuse flux from single reflections gathered from out-of-field angles of 0.4–1.4 degrees that are reflected into the FOV (‘single reflections’), contribute ~7% of the in-FOV flux (Lumb et al. (2002)), and the effective area of one of the telescopes is approximately 3 cm² at 20–80° off-axis (Freiberg et al. (2004)). OOT events are smeared along the readout direction from the bright X-ray sources of X-rays (Freiberg et al. (2004)).

2.3.2. Soft X-ray photons

Soft X-rays originate from the Local Bubble, Galactic Disk, Galactic Halo, the Solar Wind Charge Exchange (SWCX) (Snowden et al. 2004) single reflections from outside the FOV and OOT events (PN only). The SWCX is an interaction between the highly ionised solar wind and either interstellar neutrals in the heliosphere or materials in the Earth’s exosphere. There is little variation seen in the soft X-ray BG during a single observation, although long observations may be affected by the SWCX. Variations of up to 35% are seen between observations as observation pointings differ in Right Ascension and Declination. Also, the SWCX component may effect observations differently.

The diffuse contributions from the Local Bubble, Galactic Disk and Galactic Halo have a thermal component with emission lines ~< 1 keV. The extragalactic component above 0.8 keV has an index of 1.4, whereas the galactic contribution in terms of emission and absorption varies. The SWCX component is very soft and comprises unusual OVIII/OVII line ratios and strong OVIII and MgXI features.

The soft X-ray BG component is vignetted as it is made up of genuine X-ray photons. Spatially, the only structure seen is from real astronomical objects, and the extragalactic component above 0.8 keV is spatially uniform. The SWCX is seen over the whole FOV. The single reflections and OOT events behave as those resulting from hard X-rays.

The BG has shown itself to be extremely complicated and made up of various different components. When performing detailed XMM-Newton EPIC analysis, a good knowledge of the background is required. Sometimes it may be possible to extract the background from a region close to the particular source one is interested in (using a so-called ‘local’ background). For a large or extended source however, one may have to extract the background far from the target source (the source may in fact be so extended, that no local background is visible within the field of view). Here, a number of effects, due to many of the features described above, can cause the extracted local (off-axis) background to be highly inappropriate in analysing the (normally on-axis located) target source, such as changes in the effective area of the mirrors with off-axis angle, instrumental fluorescence and the spectral response which can depend on the position on the detector (these off-axis effects are corrected in the XMM-Newton EPIC calibration). Hence the need for blank sky background event files for the general user to study diffuse and extended sources, where images from XMM-Newton do not provide suitable selection areas for background subtraction.

3. Blank sky analysis

The data processing described here has resulted in the production of new XMM-Newton background event files for the 3 EPIC instruments in their different instrument mode/filter combinations. These have been constructed using a superposition of many pointed observations of pipeline product data from the Second XMM-Newton Serendipitous Source Catalogue (2XMMp) reprocessing: (http://xmm.esa.int/external/xmm_user_support/documentation/uhb/node141.html) and have been processed with the latest version of the SAS, SAS 6.5.0.

These files are available at the website location as mentioned in the introduction.

In the case of PN, in full-frame mode, for the medium and thin filter, it was necessary to split the event files, as the size of these files exceeded that of the maximum that is us-
able with FTOOLS and the XMM-Newton Science Analysis System (SAS). This is explained in more detail below.

In total 189 observations were analysed from the 2XMMp reprocessing. The observations were selected based on the absence of a large diffuse component or significantly bright source whose wings could still contaminate the background after source subtraction. Observations with bright central sources were avoided. Therefore observations of fields such as the Lockman Hole, Hubble Deep Field North and Marano pointings etc. were of particular use, and the archive was scanned for lockman hole events etc. were of particular use, and the archive was scanned for Lockman Hole, Hubble Deep Field North and Marano pointings etc. were of particular use, and the archive was scanned for useful survey fields. All available observations that were used by previous background studies (Read and Ponman (2003), Nevalainen et al. (2005), Lumb et al. (2002)) were included.

Table 1 lists the observations used in this analysis.

The final event lists result from the stacking of pipeline product event lists from many observations that have been subjected to various filtering steps, which includes the removal of sources (as described below). Therefore proper consideration of the exposure maps is required when using the final event list that applies to a set of combined observations.

Each observation was subjected to the same initial analysis. The steps in this procedure were as follows:

- The relevant 2XMMp pipeline processing system products (PPS) (event lists, attitude files, background time series, source files and calibration index files) are collected together.
- For each instrument, region files are created from the PPS source lists. These are then used to remove all the source events from each of the relevant event files. A conservative extraction radius of 35′′ is used to remove the sources (for comparison, Read and Ponman (2003) used 36′′ and Lumb et al. (2002) used 25′′). These regions are also removed from previously created mask files (these are required to calculate losses in area due to source removal).
- A visual inspection is made of the data to make sure that there are no strange features in the field (such as the rings seen from off-axis single reflections), and to ascertain whether there are any wings of very bright point sources or large diffuse sources which could contaminate the background, even after source subtraction. Datasets which fail this inspection are rejected from any subsequent analysis.
- The event files are then filtered further. Events with energies below 100 eV are discarded. For PN, only singles and doubles are retained, for MOS 1 and MOS 2, singles, doubles, triples and quadruples are retained. Finally, the event lists are filtered using the SAS-recommended #XMMEA_EM and #XMMEA_EP FLAG expressions, excepting that events from outside the field of view (out-FOV) are also kept.
- Each of the event files are then conservatively filtered for periods of high background (solar proton flares) by first creating Good Time Interval (GTI) files from the pipeline processing products background time series files and then applying these GTI files to the event file. Upper count rate threshold of 60 (PN) and 2 (MOS1/MOS2) ct/s are used as recommended as conservative thresholds by the EPIC instrument teams.
- In the case of PN, it was necessary to further filter the files to clean a small number of persistent bad (bright) pixels/columns, occurring in many (though not all) of the observations. Events were removed from all PN datasets below 250 eV, as follows: CCD1 col.13 & pixels RAWX,Y=(56,75), CCD2 RAWX,Y=(46–47,69–72), CCD5 col.11 & RAWX,Y=(41,182–184), CCD7 col.34, CCD10 col.61, CCD11 RAWX,Y=(47–48,153–156) & RAWX,Y=(50,161–164). No bad pixels were removed from any of the MOS datasets. The event files are now filtered and have had all sources removed.
- Ghosting of events, if applicable, is applied by an IDL code (see section 3.1). The use of this procedure results in refilled event list, after the completion of the tasks below. Therefore there are two types of final files: refilled files that have gone through the ghosting procedure, and unfilled files that have not.
- For each of the three instruments, a non-vignetted and vignetted 4″ exposure map is created. For the unfilled sets, the procedure was more complex than that of the filled sets, as the sources removed had to be taken into account. From the source-removed mask file, an area map (4″ binning) is created, containing zero values at the positions where sources have been removed, and unity values elsewhere. This is combined with the 4″ exposure map to create a source removed exposure map.
- To each event, values of Right Ascension and Declination are given in newly formed columns, using the information from the original event file header RA_PNT and DEC_PNT keywords.

3.1. Ghosting of events

There are two types of background event lists; unfilled and refilled. In the case of the refilled event lists, a method has been developed to ‘fill in’ the source regions that are extracted from each individual observation by sampling events close to the extracted regions, copying these events and filling the vacated region of the event list, randomising just the spatial(DETX, DETY) coordinates. Great care was taken when making adjustments for region crossovers, instrument boundaries and chips edges. This results in smooth event file images and exposure maps. Both types of event file are available at the aforementioned website, with corresponding vignetted and non-vignetted exposure maps. As the ghosted events in this code are based on DETX, DETY coordinates, it is necessary to use the SAS task attcalc, setting right ascension, declination and pointing angle to (0, 0, 0) to re-project these events in terms of X and Y. Figure 1 shows an example individual observation prior to and post the ghosting procedure. Figure 2 shows an image created from one of the final PN files made up of event files that have been subjected to the ghosting procedure, between 7.8 keV and 8.2 keV, which illustrates that the ghosting procedure slightly blurs the edges of the ‘copper hole’ as described in section 2.1.2 but is still of minimal significance. It is hoped in the future that we will be able to develop the ghosting procedure to ghost bad columns and pixels (see Section 6).
Fig. 1. Images from a PN observation with the source holes removed prior to the ghosting procedure (left) and after the ghosting procedure (right). Although there are slight problems in the ghosting procedure in very source confused areas, no problems remain after stacking of several such filled event files.

Fig. 2. An image created from one of the final refilled event files for PN, thin filter, full-frame mode, between the energies of 7.8 keV and 8.2 keV. This shows the copper hole and the slight blurring of the edges of this feature due to the ghosting procedure.

3.2. Properties of the observations used

Some features of the data sets used for MOS1 can be seen in figure 3. The equivalent figures for MOS2 and PN look essentially identical. Figure 3(a) shows a histogram of the livetime values for MOS1 after cleaning. The average values of livetimes after cleaning were 21647 seconds for MOS1, 21682 second for MOS2 and 20357 seconds for PN, hence the files are very representative of the XMM-Newton average exposure of ~22950 seconds (based on ~11200+ EPIC exposures). Observations were taken for all instruments from between revolution 70 and 691, and hence cover a good fraction of the mission. The distribution of revolution numbers for MOS1, is shown in Figure 3(b). This figure also plots a histogram of the fraction of time removed per observation, and also the fraction of time removed per month, for MOS1 (3(c) and 3(d)). The average fraction of time removed for MOS1 was 0.8098, 0.8190 for MOS2 and 0.9577 for PN, which reflects the conservative cutting levels used in the cleaning. There is no evidence that the month of the observation affects the fraction of time removed from the observation. Figure 3(e) shows a histogram of the column density values towards each MOS1 pointing. The column density values have a peak at ~2.5x10^20 cm^-2, which is very typical for an average XMM-Newton pointing. Figure 3(f) shows the total livetimes after cleaning for MOS1 per month. There is a fairly even distribution of observations throughout the year.

Figure 3 displays histograms of the fluxes of the sources removed during the cleaning procedure, for each instrument-filter-mode combination. The wide range in observation times used here has led to the low flux edges being rather shallow, i.e. no particular single flux limits exist above which sources have been removed. For a general user, this could lead to some data extracted from the BG event files as being not entirely appropriate – there possibly being slightly too little of too much emission from low-flux sources within the extracted BG data. Future plans for this project (see Section 6) include the addition of software able to select BG events files from the full BG dataset of observations, based on the component observation’s exposure time. This can lead to BG files with tighter, steeper source flux limit cut-offs, perhaps more appropriate to a user’s own single dataset.

3.3. Production of the final files

After the procedure described above was completed for each of the 189 observations, the individual files were reviewed to ensure that no bright sources remained, relevant event files for each instrument-filter-mode combination were merged together to form the final sets (Table 2). Each merged file was subjected to a call to attcalc to set the right ascension, declination and position angle to (0, 0, 0). In these final files one will find the primary header, events extension, exposure extensions and GTI extensions. There are 12 exposure and 12 GTI extensions for PN and 7 of both types for each MOS. Keywords that are applicable to only individual observations, such as DATE_OBS and EXPIDSTR were removed from each file extension. The keywords for LIVETIME, LIVETIMEn, ONTIME, and ONTIME0n, where n is the number of the CCD, were recalculated and added to the headers of the final file as appropriate. All keywords that are mandatory for OGIP FITS (OGIP_93_003) standards were assured to be present and adjusted. For example the keyword REVOLUT was set to 0000, OBS_JD was set to 0000000000 and EXP_JD was set to 000000000000.

For both unfilled and refilled PN event files, in the full-frame mode and either the medium or thin filter, it was found that the resultant final file exceeded the size limits for use with the XMM-SAS. It was necessary, therefore to split these
Fig. 3. Properties of all the files used to construct the MOS1 blank sky event files; (a) histogram of livetimes, (b) histogram of revolution numbers, (c) fraction of time removed during cleaning, (d) fraction of time removed per month, (e) histogram of nH values in the direction of pointing for an observation and (f) total livetime after cleaning per month.

files so that they could be usable, and a decision was made to split them based on location on the sky of the events. The files roughly split into hemispheres centred about the galactic centre and the galactic anti-centre as a variation between these two locations is seen in spectral shape, as described in section 4. We here used the addition of the right ascension and declination (RA and DEC) columns added to the component event files in the individual observation processing, which then later appear in the final event files.
Fig. 4. Flux histograms of the removed sources for each of the instrument-filter-mode combinations data sets, where M1=MOS1, M2=MOS2, F=full-frame mode, E=full-frame-extended mode, T=thin filter, M=medium filter and K=thick filter. The y-axis represents the number of sources removed from the data sets for a particular flux.

For both the unfilled or refilled event lists, this has resulted in the production of 14 final background event files. For each event file there is a corresponding non-vignetted and vignetted exposure map. Therefore there are 84 files in total (42 for either unfilled or refilled procedures).

Table 2 summarises the resulting background event files, detailing the number of component observations used and the overall exposure time.

These final event files offer several improvements over previous blank sky background event files. The ghosting procedure is an addition to the previous work and we have taken advantage of the new 2XMMp reprocessing products and improved general knowledge of the BG to improve the cleaning of each file. These files are found at: http://xmm.vilspa.esa.es/external/xmm_sw_cal/background/index.shtml.

The site includes a description of the naming convention of these files. Images created from the final filled event files can be seen in Figure [S].

4. Properties of the blank sky event files

Some basic analysis was performed on the blank sky event files. The following features of these data sets should be taken into account when using the files.

4.1. Variations in spectral shape with count rate

Spectra were produced selecting the time intervals for low, medium and high count rates, using good time intervals between 10 keV and 12 keV. Spectra were taken within a circle of radius 8.3’ between 0.3 keV and 8 keV. Using MOS1, thin-
Table 1. Summary of all the observations used. IMF gives the instrument, mode and filter for PN-MOS1-MOS2 as [f=full-frame, ft=full-frame-extended, t=thin, m=medium, k=thick and NA = not applicable]. Exp is the cleaned exposure time, and f(Ex) the fraction of exposure removed after screening (where possible PN or alternatively MOS1).

| IMF | Exp(s) | f(Ex) |
|-----|--------|-------|
| 01123001 | 46051 | 0.002 |
| 10112902 | 39999 | 0.015 |
| 01124904 | 5898 | 0.000 |
| 01279209 | 14699 | 0.000 |
| 01092401 | 13300 | 0.000 |
| 01123710 | 25247 | 0.002 |
| 01293209 | 5039 | 0.000 |
| 01129707 | 19519 | 0.000 |
| 01446003 | 9699 | 0.000 |
| 01091009 | 50256 | 0.046 |
| 01345130 | 6024 | 0.000 |
| 01129209 | 9514 | 0.044 |
| 00974220 | 9400 | 0.000 |
| 00934609 | 5899 | 0.007 |
| 00867059 | 9155 | 0.000 |
| 00734202 | 9949 | 0.000 |
| 00061031 | 31929 | 0.000 |
| 01115902 | 41095 | 0.012 |
| 01115504 | 91805 | 0.005 |
| 01096608 | 62485 | 0.074 |
| 01096610 | 80857 | 0.077 |
| 01111003 | 20010 | 0.000 |
| 01111003 | 20099 | 0.000 |
| 01122503 | 21999 | 0.000 |
| 01112201 | 37390 | 0.000 |
| 00090101 | 26481 | 0.100 |
| 01219104 | 9942 | 0.000 |
| 00022701 | 26085 | 0.102 |
| 01124908 | 15664 | 0.000 |
| 00509403 | 9098 | 0.000 |
| 00501503 | 25133 | 0.060 |
| 00092360 | 9935 | 0.000 |
| 00217401 | 29888 | 0.021 |
| 00293600 | 7399 | 0.000 |
| 00280800 | 14277 | 0.000 |
| 00287403 | 25863 | 0.000 |
| 00867500 | 8895 | 0.000 |
| 01092401 | 19653 | 0.000 |
| 01124800 | 21919 | 0.000 |
| 00160604 | 43941 | 0.000 |
| 01219601 | 13906 | 0.000 |
| 00335400 | 9912 | 0.000 |
| 01125505 | 18499 | 0.000 |
| 01218501 | 13000 | 0.000 |
| 00079802 | 8999 | 0.000 |
| 00079807 | 7999 | 0.000 |
| 00079809 | 7999 | 0.000 |
| 01128604 | 21991 | 0.000 |
| 00083901 | 23222 | 0.000 |
| 00081200 | 13533 | 0.000 |
| 00362401 | 2392 | 0.000 |
| 00516100 | 17960 | 0.000 |
| 00821403 | 62485 | 0.074 |
| 01122800 | 4999 | 0.000 |
| 01122800 | 4999 | 0.000 |
| 01122800 | 4999 | 0.000 |
| 01122800 | 4999 | 0.000 |

4.2. Variation of out-FOV count rate

For each of the unfilled event lists, the out-of-field-of-view (out-FOV) count rate, essentially the cosmic-ray induced instrumental background, was calculated for both events with pattern 0, and events with patterns ≤ 12 for MOS and events with patterns ≤ 4 for PN, using spectra created between the energies of 2.5 keV and 6.0 keV, to avoid the instrumental lines and just show the continuum. The out-FOV count rates representing the quiescent particle (instrumental) background, are given in Table 3.

The count rates for MOS1, MOS2 and PN show an expected increase when looking at the rates from those patterns ≤ 12, or 4 in the case of PN, compared to those with pattern...
Table 2. Summary of the cleaned and filtered observations used in the production of the EPIC background files, separated into the different combinations of instrument, instrument mode and filter used. LIVETIME is the livetime keyword value for the central CCD i.e. corrected for periods of high-background and dead-time. For the PN full-frame mode with the medium or thin filter, the files have been split between the two hemispheres based on the galactic centre and galactic anti-centre individual event pointings.

| Instrument | Mode          | Filter | Location if applicable | Number of Observations | LIVETIME (s) |
|------------|---------------|--------|------------------------|-------------------------|--------------|
| MOS1       | Full-Frame    | Thin   |                        | 113                     | 2194330      |
| MOS1       | Full-Frame    | Medium |                        | 65                      | 1583390      |
| MOS1       | Full-Frame    | Thick  |                        | 12                      | 305700       |
| MOS2       | Full-Frame    | Thin   |                        | 112                     | 2087800      |
| MOS2       | Full-Frame    | Medium |                        | 67                      | 1679900      |
| MOS2       | Full-Frame    | Thick  |                        | 13                      | 343773       |
| PN         | Full-Frame    | Thin   | total                  | 42                      | 993370       |
| PN         | Full-Frame    | Thin   | anti-centre            | 21                      | 536349       |
| PN         | Full-Frame    | Thin   | centre                 | 21                      | 457021       |
| PN         | Full-Frame    | Medium | total                  | 33                      | 1078113      |
| PN         | Full-Frame    | Medium | anti-centre            | 12                      | 574272       |
| PN         | Full-Frame    | Medium | centre                 | 21                      | 503841       |
| PN         | Full-Frame    | Thick  |                        | 10                      | 237458       |
| PN         | Full-Frame-Extended | Thin | total                  | 62                      | 825204       |
| PN         | Full-Frame-Extended | Medium |                        | 30                      | 461575       |
| PN         | Full-Frame-Extended | Thick |                        | 3                       | 58664        |

Fig. 6. Spectra plotted based on differences in count rate between 0.3 keV and 8 keV for MOS1, in full-frame mode using the thin filter. Black shows the highest count rate, red is classed as the medium count rate spectrum, and green the lowest count rate spectrum.

Differences in count rates are seen between the PN full-frame mode event files (both thin and medium filter), selected on the basis of their sky position – i.e. Galactic centre or Galactic anti-centre – the Galactic centre count rates being somewhat larger. It was initially thought that this difference might be due to the time of year of the individual observations, there being some evidence that summer observations are, on average, more heavily affected by solar flare activity than winter observations. A higher summer-to-winter exposure time ratio for the Galactic centre observations, compared to the Galactic anti-centre observations, could be indicative of relatively worse solar flaring in the Galactic centre observations. These ratios however are not particularly different for the two position-dependent subsets, and thus there is little evidence that this hypothesis is correct. We note though that the numbers of observations in each of the subsets is rather low, and small number statistics and the actual pointings of the individual observations may well be the cause of the observed differences. Indeed, on ignoring outlying observations with high count rates, the ratio between centre and anti-centre is greatly reduced.

4.3. Variation of in-FOV count rates

Similar to the analysis of out-FOV, in-FOV count rates were also taken from spectra between 2.5 keV and 6.0 keV to avoid the instrumental lines, using a circle of 10′, with a pattern selection as before as used for the out-FOV count rates. These values were calculated for the refilled event files to avoid the use of the complicated exposure maps in calculation of the areas used and are also shown in Table 3. For each instrument-filter-mode combination, the in-FOV count rates are higher than those of the out-FOV, as expected as these in-FOV values result from both photon and particle contributions. The MOS cameras are
Table 3. Out-FOV and in-FOV count rates for the refilled background event files between 2.5 keV and 6.0 keV. The pattern code gives the patterns used, and can be either equal to 0, ≤ 12 (MOS) or ≤ 4 (PN). For the mode/filter combination a code is used, and for some PN files the location dependent of the file is indicated where appropriate [f - full-frame mode, e - full-frame-extended mode, t - thin filter, m - medium filter, k - thick, AC - galactic anti-centre hemisphere, GC - galactic hemisphere].

|Instr Mode/Filt./location if applicable | Pattern code | Out-FOV count rate (2.5−6 keV) (ct/s/arcmin²)×10⁻⁴ | In-FOV count rate (2.5−6 keV) (ct/s/arcmin²)×10⁻⁴ |
|---------------------------------------|-------------|------------------------------------------------|------------------------------------------------|
| M1 ft 0                               | 2.69        | 5.74                                           |
| M1 ft 12                              | 4.01        | 8.17                                           |
| M1 fm 0                               | 2.80        | 6.92                                           |
| M1 fm 12                              | 4.15        | 9.80                                           |
| M1 fk 0                               | 2.68        | 3.52                                           |
| M1 fk 12                              | 4.02        | 5.11                                           |
| M2 ft 0                               | 2.87        | 5.92                                           |
| M2 ft 12                              | 4.21        | 8.92                                           |
| M2 fm 0                               | 2.93        | 6.70                                           |
| M2 fm 12                              | 4.29        | 9.34                                           |
| M2 fk 0                               | 2.88        | 3.48                                           |
| M2 fk 12                              | 4.22        | 4.96                                           |
| PN et 0                               | 20.4        | 37.2                                           |
| PN et 4                               | 31.2        | 58.4                                           |
| PN em 0                               | 31.3        | 62.2                                           |
| PN em 4                               | 48.1        | 98.0                                           |
| PN ek 0                               | 11.8        | 17.3                                           |
| PN ek 4                               | 17.7        | 26.8                                           |
| PN ft AC 0                            | 25.4        | 47.7                                           |
| PN ft AC 4                            | 39.1        | 74.9                                           |
| PN ft GC 0                            | 34.2        | 64.1                                           |
| PN ft GC 4                            | 52.6        | 101.0                                          |
| PN fm AC 0                            | 27.7        | 45.3                                           |
| PN fm AC 4                            | 42.6        | 71.1                                           |
| PN fm GC 0                            | 39.5        | 80.1                                           |
| PN fm GC 4                            | 61.0        | 126.5                                          |
| PN fk 0                               | 19.0        | 31.3                                           |
| PN fk 4                               | 28.9        | 49.0                                           |

consistent with each other. The PN in-FOV count rates are higher than those of the MOS. The PN in-FOV count rates for those files split into the galactic centre and galactic anti-centre events show the same feature as the out-FOV, namely that the galactic centre has higher count rates than the anti-centre. The factor by which the Galactic Centre count rates are greater than the Galactic anti-centre count rates is larger in-FOV than out-FOV (as expected, given that photons, soft protons and particles contribute in-FOV, whereas only [mostly] particles contribute out-FOV). As discussed with respect to the out-FOV count rates however, there is no evidence that it is a time-of-year effect that is causing these differences, but it can be explained via statistical fluctuations and the relatively low number of observations used.

An indication of the spectral differences in- and out-FOV, and how these differences can lead to severe problems when trying to subtract the instrumental background, is shown in Fig. 7 Here, MOS1 and pn spectra are shown extracted from the in-FOV region, together with spectra showing the difference between the in-FOV spectrum and an extracted, area-scaled out-FOV spectrum. Strong instrumental BG lines at Al (1.5 keV) and Si (1.7 keV) are seen in the MOS spectrum, together with weaker features at Cr (5.4 keV), Mn (5.8 keV), Fe (6.4 keV) and Au (9.6 keV). The PN spectrum shows a strong instrumental line at Al (1.5 keV) and a strong high-energy line at Cu (8.0 keV), plus weaker high-energy lines at Ni (7.4 keV), Cu (8.6 keV) and Zn (9.0 keV).

The 'difference' spectra should, ideally, show what remains once the instrumental BG has been removed, i.e. a smooth photon BG distribution. However this is not the case, and sharp features are seen in the 'difference' spectra at the positions of the instrumental lines. This is due to the distribution of the emission from the various fluorescent lines varying across the detectors, as discussed in Sect. 2.1.2. For MOS, there is relative deficit of Al in-FOV compared to out-FOV, hence the ‘difference’ spectrum shows a trough. For Si, the situation is reversed and a peak in the difference spectrum is observed. Similarly Au (2.2 keV) and Fe are relatively enhanced out-FOV. For PN, the Al line is relatively evenly distributed across the detector, and consequently the difference spectrum shows no peak or trough.
Fig. 7. MOS1 (top) and PN (bottom) (1.0–10 keV) spectra extracted from the full-frame, thin filter BG event files. The upper spectrum in each panel is extracted from the in-FOV region, while the lower spectrum shows the difference between the in-FOV spectrum and an extracted out-FOV spectrum, scaled to account for the difference in areas. Line features in the ‘difference’ spectra indicate the differences in distribution of fluorescent line emission across the detectors, as explained in the text.

Ni and Cu however, are very much depleted at the centre of the detector, as discussed in Section 2.1.2, and strong troughs are observed in the difference spectrum.

4.4. Variation in BG with location on sky

Background events from regions of the sky have been selected from four coordinate centres using the script SelectRADec (see section 5): the galactic centre, galactic anti-centre, the south galactic pole and the north galactic pole. Spectra were then produced for each region and plotted in Xspec using a canned response matrix, for example for MOS1 thin filter, full-frame mode as shown in Figure 8.

Note that the galactic centre shows a higher count rate at between approximately 0.3 keV to 3 keV due to increased soft X-ray emission in the galactic plane and centre.

5. Using the Background files

Several useful scripts that can be used with the background event files described in this paper, are found at the BGWG web page. The scripts are described below.

5.1. Script: Skycast

This script is used to cast an XMM-Newton EPIC background dataset (or indeed any EPIC event dataset) onto the sky, at the position given by an input template event dataset (e.g. the event file for which one is interested in producing a background). This is useful as the user is more likely to be working in sky coordinates than instrument coordinates.

5.2. Script: SelectRADec

This script can be used to select events from a certain area of the sky, specifying a right ascension and declination (J2000), and the maximum distance from this position one is prepared to consider. A final event file and exposure map is produced. This may be useful to a user whose is concerned about the dependence of the background with location, as shown in Figure 8.
This script is used to rebin and re-project the provided exposure maps onto the sky to the spatial scale and sky position of a user-input image. This is useful when wanting to work in sky coordinates and to a different spatial scale than the 4″ scale used in the production of the exposure maps.

5.4. Using the Background files: Reliability

In this final subsection on the use of the BG files, we have attempted to provide a gauge of the reliability of the Blank Sky files. To achieve this, and to mirror how these files might be used by the community, we have performed a typical BG analysis that a general user might perform, but on separate subsets of the same blank sky event files, and compared the results obtained, i.e. employing a ‘cross-validation’-like technique. For each analysis, two large time-separated sub-event files were extracted from a particular BG event file, each covering 40–50% of the original exposure time. These two event files were then screened (further) for times of medium-high soft proton flares, as a user would wish to do (the event files having been earlier screened for times of high soft proton flares – see Sect.3). For each flare-filtered sub-event file, a ‘source’ spectrum was extracted from a 6″ radius circular in-FOV central region of the instrument. A ‘background’ spectrum was also extracted from the out-FOV ‘corners’ of the detector. Here then, the ‘source’ spectrum should contain (predominantly) both photon and particle components of the EPIC BG, whereas the ‘background’ spectrum should contain just the particle component of the EPIC background. Correct analysis and subtraction of one from the other should yield just the extragalactic photon X-ray background.

For the MOS cameras, the out-FOV regions of the detectors are quite large, and hence reasonable instrumental BG statistics can be obtained from these areas (in actuality, we used the MOS out-FOV regions as defined in de Luca & Molendi (2004)). For the pn however, the situation is much worse, as the out-FOV regions are very much smaller and close to the noise of the pn readout. The very limited statistics obtained from the pn out-FOV regions make instrumental BG subtraction very problematic. Furthermore, for the pn, the response varies along each CCD due to charge transfer inefficiency effects, making any determination of a linear response with position and radial vignetting a very complicated problem (e.g. Lumb et al 2002). The recent addition of long-exposure stacks of closed filter full-FOV pn data (dominated by the instrumental BG) to the official ESA web pages (http://xmm.vilspa.esa.es/external/xmm_sw_cal/background/index.shtml) will help in the future to allow a much better determination and subtraction of the in-FOV instrumental BG component. This is beyond the scope of the present paper however, and we have here concentrated on the MOS data.

The analysis using the large, MOS, thin filter, full-frame BG event files is described here. Once the spectra were formed, as above, appropriate RMF response matrices and ARF auxiliary files were created using XMM-Newton SAS 7.0 and the source spectral channels were binned together to give a minimum of 20 counts per bin. Spectral fitting was performed using Xspec, incorporating a photo-electric absorption times power-law (wabs×power-law) model. The hydrogen column density of the absorption component was fixed in each case to the exposure-weighted average of the hydrogen column densities of the component observations (see Sect.3.2). The power-law spectral index and normalization were allowed to go free. Fitting was performed in the energy range 2.5–6.0 keV, i.e. concentrating on the line-free continuum area of the spectrum. The spectral analysis results are summarized in Table 4. Tabulated, both for MOS1 and MOS2, are the best-fitting power-law spectral index and normalization for each ‘half’ of the original full-size thin filter, full-frame BG event files. Errors are 1σ for one interesting parameter. As can be seen, the fitted indices and normalizations for the two halves are consistent with one another, both for MOS1 and for MOS2. Furthermore, the values obtained for MOS1 are consistent with the values obtained for MOS2. And finally, the actual values of power-law index obtained are consistent with the generally accepted value for the power-law index of the true extragalactic X-ray background (≈ 1.42; e.g. Lumb et al 2002). This analysis therefore, indicates that the BG event files presented here are consistent (both with each other and with other external measures of the X-ray BG) and reliable (both between files and internally within individual files).

### Table 4. Results of spectral fitting to the two subsections of the MOS thin filter, full-frame mode background files, fitted using a wabs×power-law model (see text).

| Instr | Subsection | Photon Index | Normalisation |
|-------|------------|--------------|---------------|
| M1    | 1          | 1.37±0.15    | 7.64±1.50     |
| M1    | 2          | 1.45±0.15    | 10.5±1.90     |
| M2    | 1          | 1.42±0.07    | 12.2±1.17     |
| M2    | 2          | 1.50±0.19    | 9.62±2.30     |

6. Conclusions and future developments

We have described in detail the components that make up the XMM-Newton EPIC background and why a good understanding of this background is important. We have explained the steps behind the production of blank sky event lists that are available for the general user via the XMM-Newton EPIC background working group website, and are useful for background analysis. We have presented several interesting features of these files including variations in spectral shape with count rate and variations in count rate between out-FOV and in-FOV areas. Finally we have presented software that can be used with the blank sky event files and associated exposure maps, also available via the background working group web pages.

It is hoped that in the near future more 2XMM datasets will become available that fulfil the criteria previously described for the background sets. These will then be filtered as appropriate.
and merged with the existing datasets. We also hope to improve the ghosting procedure as described in Section 3.1 to incorporate the inclusion of bad pixels and columns, and to provide a means to select background events based on their component observation exposure time, as described in Section 3.2. A tool to select sections of the event files as based on count rates may become available in the near future, to accompany the tools already available.

Further releases of modified datasets will be announced via the URL:
http://xmm.esac.esa.int/external/xmm_sw_cal/background/index.shtml.

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Fig. 5. Images of the final unfilled event files for each instrument-filter-mode combination, between 0.3 keV and 12 keV for the PN and from between 0.2 keV and 12 keV for the MOS cameras. The PN event files for full-frame mode, with the medium or thin filters have been split into those events centred about the galactic centre, and those centred about the galactic anti-centre.