Analysis of the Unconcentrated Background of the EPIC pn Camera on Board XMM-Newton

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Abstract
Our understanding of the background of the EPIC/pn camera on board XMM-Newton is incomplete. This affects the study of extended sources and can influence the predictions of the expected background of future X-ray missions, such as the Advanced Telescope for High Energy Astrophysics (ATHENA). Here we provide new results based on the analysis of the largest data set ever used. We focus on the unconcentrated component of the EPIC/pn background, supposedly related to cosmic rays interacting with detector and telescope structures. We show that the so-called out-field-of-view region of the pn detector is actually exposed to the sky. After carefully cleaning from the sky contamination, the unconcentrated background measured in the out field-of-view region does not show significant spatial variations, and its time behavior is anticorrelated with the solar cycle. We find a very tight linear correlation between unconcentrated backgrounds detected in the EPIC/pn and EPIC/MOS2 cameras. This relationship permits the correct evaluation of the pn unconcentrated background of each exposure on the basis of MOS2 data, avoiding the use of the contaminated out-field-of-view region of the pn, as done in standard techniques. We find a tight linear correlation between the pn unconcentrated background and the proton flux in the 630–970 MeV energy band, as measured by the EPHIN instrument on board SOHO. Through this relationship, we quantify the contribution of cosmic-ray interaction to the pn unconcentrated background. This reveals a second source that contributes to the pn unconcentrated background for a significant fraction (30%–70%). This agent does not depend on the solar cycle or vary with time and is roughly isotropic. After having ruled out several candidates, we find that the hard X-ray photons of the cosmic X-ray background satisfy all known properties of the constant component. Our findings provide an important observational confirmation of simulation results on ATHENA and suggest that a high-energy particle monitor could contribute decisively to the reproducibility of the background for both experiments on ATHENA.

Unified Astronomy Thesaurus concepts: Particle astrophysics (96); Astronomy data analysis (1858); Diffuse x-ray background (384); X-ray detectors (1815); X-ray astronomy (1810)

1. Introduction
For the last 20 yr, the XMM-Newton observatory (Jansen et al. 2001) has been providing the largest collecting area of any imaging X-ray telescope flown to date. This large collecting area is exploited by the European Photon Imaging Camera (EPIC) detector, composed of a pn (Strüder et al. 2001) and two MOS CCD cameras (Turner et al. 2001) at the focus of its three X-ray telescopes. The EPIC capabilities of characterizing low surface brightness emission from extended and faint objects, such as supernova remnants and clusters of galaxies, are highly affected—more than expected before the launch—by a high and variable background (e.g., Lumb et al. 2002; Read & Ponman 2003; de Luca & Molendi 2004) that is still poorly understood. The characterization of low surface brightness emissions is also among the top science goals for the Advanced Telescope for High Energy Astrophysics (ATHENA), the future large mission of the ESA dedicated to the X-ray band that is to be launched in the early 2030s. To achieve this goal, it is vital to minimize the intensity of the background that will affect ATHENA and maximize its reproducibility during the current phase of mission design, orbit evaluation, and definition of the observational strategy. As discussed in Molendi (2017), much can be learned from previous X-ray missions. In this respect, XMM-Newton is particularly useful both because its EPIC pn camera bears strong similarities to the ATHENA WFI instrument and because during most of its highly elliptical orbit, it is not shielded by the Earth’s magnetic field and thus is affected by high-energy galactic cosmic rays, as ATHENA will be in its orbit around L1 or L2.5

The EPIC background can be divided into three main components: the background due to noise and defects of the detectors, the component concentrated by mirrors (X-ray photons and low-energy protons), and the unconcentrated component (mainly consisting of high-energy particles and their secondaries).

The detector background comprises electronic noise (e.g., readout noise, dark current) and damaged pixels/columns. The first part is important at low energies (i.e., below 300 eV), while the second part is limited to specific small areas of the detector (bright pixels and columns).

The concentrated background is produced by two components: photons and soft protons (SPs). The photon background is due to the emission of unresolved active galactic nucleus (the cosmic X-ray background, CXB), of unresolved galactic

5 L2 is the original baseline orbit for ATHENA. Based on the analysis of the available data on SPs at L1 and L2, the Athena Science Study team recently recommended an L1 orbit. The final decision will be made within a few months.
extended sources and of the Galaxy itself. Their overall rate is almost time-independent and depends only on the sky region within the field of view (FOV). Low-energy protons (with energies smaller than a few hundred keV) are funneled toward the detectors by the X-ray mirrors and detected as events; this component is characterized by strong (up to 3 orders of magnitude) and rapid (down to a few tens of seconds) variability.

The unconcentrated background is mainly due to the interaction of high-energy particles (typically cosmic rays with energies larger than some 100 MeV) with the structure surrounding the detectors and the detectors themselves. Part of the particles (e.g., the minimum ionizing particles, MIPs) are recognized, and the events ascribed to them are rejected on board the satellite, resulting in time-dependent excluded CCD columns and/or events with invalid patterns (i.e., illuminating nearby pixels spatially distributed differently than expected for valid X-ray events).

Knowledge of these components has been improving thanks to the many efforts involved in collecting suitable blank sky fields to be used as template backgrounds by XMM-Newton users (Read & Ponman 2003; Carter & Read 2007); this led to the XMM-Newton Extended Source Analysis Software (Kuntz & Snowden 2008; Snowden et al. 2008). Our team has been particularly active on this topic (de Luca & Molendi 2004; Gastaldello et al. 2007; Leccardi & Molendi 2008), and we have recently exploited a large data set of MOS2 observations to further advance the knowledge of the XMM-Newton focused and unfocused background components (Gastaldello et al. 2017; Ghizzardi et al. 2017; Marelli et al. 2017; Salvetti et al. 2017). These latter works were developed in the framework of the R&D ESA project ATHENA Radiation Environment Models and X-Ray Background Effects Simulators (AREMBES) and contributed to estimating the expected background level of ATHENA detectors and favoring the baseline orbit around L1 rather than L2.

All of these studies were focused mainly on the MOS cameras. A key feature of these detectors is the presence of portions that are not exposed to the sky (out field of view, outFOV), so neither celestial X-ray photons nor SPs focused by the mirror are collected there. This continuous monitoring of the unconcentrated background allows one to also evaluate such components in the focused area, where celestial photons and SPs dominate.

The pn background has been studied in Freyberg et al. (2004), Fraser et al. (2014), and Katayama et al. (2004). The differences that make the pn analysis more difficult with respect to that of the MOS are the relatively small outFOV detector area—about a quarter that of MOS2—and the higher percentage of out-of-time (OoT) events (from 2.3% to 6.3% for the pn as opposed to 0.35% for the MOS). Such an effect is due to the CCD transfer time; a minor fraction of in-field-of-view (inFOV) events is incorrectly assigned to the outFOV region as OoT events.

With these differences in mind, our team tackled the issue of studying the unconcentrated background in the pn camera making use of events falling in the outFOV, as we did for the MOS2 camera. To this aim, we took advantage of the big data sets available within the R&D ESA project AREMBES and the FP7 European project Exploring the X-ray Transient and variable Sky (EXTraS; de Luca et al. 2016). Unfortunately, it was clear from the inspection of the first data sets that the outFOV areas of the pn are contaminated by the focused components, both photons and SPs. In Section 2, we demonstrate the presence of this contamination using small subsamples of the available XMM-Newton observations. Here we give a general idea of the characteristics and origin of this contamination that will be useful throughout the paper to minimize it in our larger sample. We present the data set we use and the event selection we adopted in Section 3, with particular care for the minimization of the contaminants (the details of the contamination effects and the minimization of such components in our event set are described in Appendices A and B). In Section 4, we present our analysis to characterize the temporal behavior of a pn unconcentrated background. In Section 5, we study the resulting time series, investigating whether different choices of filters and observing modes affect the pn background, as well as the correlation between pn and MOS2 unconcentrated backgrounds. In Section 6, we report on the analysis of the spatial distribution of the pn unconcentrated background within the outFOV. Finally, in Section 7, we discuss the results of our analysis, also correlates them with the contemporaneous time series of high-energy protons accumulated with the EPHIN detector on board the Solar and Heliospheric Observatory (SOHO; Müller-Mellin et al. 1995; Kühl et al. 2016). In Section 8, we summarize the main results of this paper.

2. The Problem of Contamination in the pn Corners

Our study of the unconcentrated background of the pn camera is based on events falling in its outFOV area. Since this is the first time that such a study has been performed, we need to check whether other background components contaminate the pn outFOV, such as concentrated photons and/or SPs. Making a first analysis of small samples, we are able to obtain a zero-order characterization of contamination and choose the best techniques to minimize it in larger samples.

We selected two different case studies: one with a large number of SPs and the other with a large number of photons distributed over the entire inFOV. The first case study (“proton sample”) is composed of a selection of long XMM-Newton observations contaminated by SPs with a total exposure of 504 ks. No bright extended sources are in the field of these observations, and the number of pointlike sources is limited. For this sample, we select and use only periods of high and variable background to maximize the SP contamination. The second case study (“photon sample”) comprises the XMM-Newton observations pointing to the center of the Coma cluster, one of the brightest, hardest, and most extended X-ray sources in the sky, with a total exposure of 115 ks. For this sample, we select and use only periods of low and constant background so as to exclude the SP contamination and magnify the photons’ contamination.

The periods of high SP background are in this respect unexceptional, as they represent 40% of the XMM-Newton time available to observations, as many studies reported and confirmed on a large data set by our work (Salvetti et al. 2017). On the contrary, the photon contamination in the pn outFOV by
the observation of the central regions of Coma is rather exceptional.

We followed the standard analysis procedure for pattern and flag selection (see, e.g., Rosen et al. 2016). We evaluated the contamination by OoT events following the procedure that will be discussed in Section 4.1. For each exposure, we extracted the count maps in detector coordinates (1 pixel = 1 arcsec$^2$). Maps from different observations were summed, and for each map, we produced a radial brightness profile centered on the geometrical center of the pn detector.

Formally, the inFOV area is defined as a circle with a 900″ radius from the geometrical center of the pn, while the remaining area is outFOV (Strüder et al. 2001). From Figure 1, it is apparent that the entire outFOV area is contaminated by photons (upper panels) and SPs (middle panels). The contamination is larger in the inner part of the outFOV and decreases following, as a first approximation, a quasi-exponential model. This is completely different from what was observed in the case of the MOS cameras; we show, as an example, the MOS2 view of the “proton sample” in the lower panels of Figure 1. The sudden drop in the count rate by more than a factor of 10 at the border of the FOV is apparent.

Since, for the pn, there is no region unaffected by the concentrated background, the use of the term “outFOV” to describe the corners of the pn is something of a misnomer, as these regions are sensitive, albeit only partially, to SPs and photons. However, faced with the choice of either adopting a new term or maintaining the term “outFOV,” we opt for the latter.

Also, it is obvious that, to extract the unconcentrated background, we cannot use all of the events falling in the outFOV region, as we did for the MOS2 camera (Marelli et al. 2017). For the analysis of the larger data set, we will adopt two different filters to mitigate the contamination by photons and SPs in the outFOV region (see Section 3). Also, the residual contamination will be evaluated a posteriori at the end of the analysis (Sections 5 and 6).

3. Data Preparation

In this section, we describe the preparation of the pn outFOV data set. The method we adopt is designed to minimize the contamination from photons and SPs shown in Section 2.

We retrieved observation data files from the XMM-Newton repository. Then we performed a standard reduction using the XMM-Newton Science Analysis Software (SAS) v.14.0 and the calibration files available from 2016. We barycentered all of the data sets using the SAS tool barycen.

3.1. Data Set

The starting point of our project is the database of XMM-Newton observations produced within the EXTraS project (de Luca et al. 2016). EXTraS is based on the fourth data release of the 3XMM source catalog, which considered all XMM-Newton EPIC exposures made between 2000 February 3 and 2012 December 8. For this analysis, we rely on the 5708 pn exposures (for a total time of ~150 Ms) with an available EXTraS background light curve. We made the following subselections.

(a) We used only observations performed in full-frame or extended full-frame modes, because in the other submodes, the outFOV area is not read.

(b) We used only exposures with an attitude stability better than 5″, as reported in the attitude files.

(c) We excluded exposures taken, even partially, during solar energetic particle events (SEPs), as defined by the ESA Solar Energetic Particle Environment Modeling application server (see Figure 10 of Gastaldello et al. 2017), since SEPs with a particularly hard particle spectrum could, in principle, affect the outFOV rate on short timescales.

(d) We excluded highly SP-contaminated exposures and revolutions in order to minimize the contamination of the outFOV area (for details, see Appendix A).

These selections lead to a final data set that we dub the “main data set.” It comprises ~93 Ms, covering 1356 XMM-Newton revolutions. In Figure 2, we display the amount of exposure time and number of revolutions excluded with respect to the initial EXTraS-based data set.

3.2. Event Selection

We optimized our event selection to minimize the detector background and the contaminating SPs and photons. To exclude the contamination of the borders due to the pixellation of the detector, we define the outFOV region as the one outside a 905″ radius circle centered on the geometrical center of the pn detector, while the inFOV region is the one within the centered 900″ radius circle. For both regions, we excluded pixels close to the CCD borders.

Following the standard analysis procedure, we applied a filter on event patterns, using only single and double events. We used standard flags to exclude events with invalid patterns or associated with cosmic rays or MIPs, secondary and trailing events, and events falling on and close to dead or bad pixels, bright pixels and bright columns. Bright pixels and columns are not the same for all exposures, since the radiation damage increases with the instrument lifetime, and some of them are not excluded using standard flags. Instead of considering each exposure separately, we chose to collect events from our entire data set and produce a total image in detector coordinates. Then, we manually selected the remaining bright or dead regions and excluded them in all exposures.

To minimize photon contamination, we use the energy band 10–14 keV, since the effective area for photons is negligible in this energy band. To minimize SP contamination in the outFOV, we also perform a time selection to exclude SP flares. We perform this filtering by applying, for each exposure, the algorithm developed for the EXTraS project on the inFOV data as described in Appendix A.

All of the expressions used to filter events through SAS are reported in Appendix C. Using these selections, we obtain an inFOV area of 28.355 cm$^2$, corresponding to 595.646 arcmin$^2$, and an outFOV area of 2.512 cm$^2$, corresponding to 52.780 arcmin$^2$. These define the inFOV and outFOV regions we use throughout this paper.

4. Time Series: Extraction and Analysis

To obtain the surface brightness $s$ (in units of counts s$^{-1}$ cm$^{-2}$ keV$^{-1}$) of the outFOV area of the pn, measured in the 10–14 keV energy band, we started from our main data set as defined in Section 3.1 and extracted events in the outFOV region of each CCD using the SAS tool evselect, with the

9 http://xmmssc-www.star.le.ac.uk/Catalogue/3XMM-DR4/

10 http://www.sepem.eu/
Figure 1. Count map (left) and radial surface brightness profiles (right) of the two pn case studies we analyzed in Section 2: the photon sample (upper panels) and the proton sample (middle panels). We also show the count map and radial profile obtained for the MOS2 camera using the proton sample (lower panels); in this case, we excluded from the radial profile analysis the regions outside the dashed circle and within the dashed sector due to the deviation from a circular geometry of the inFOV (see also Marelli et al. 2017). The border between the inFOV and outFOV regions is marked by a black circle in the images and a blue vertical line in the brightness profiles. In the brightness profiles (right panels), we show the area-normalized count rate (black points) and, for the two pn data sets, the predicted OoT events (gray points). In red, we also show the best fit of the pn outFOV region using, as a first approximation, a constant plus exponential model.
The mean count rate in the outFOV region of the pn is 0.053 counts s$^{-1}$, similar to the one obtained for the MOS2 outFOV, 0.071 counts s$^{-1}$ in the 7–9.4 and 10–11 keV energy bands (Marelli et al. 2017). Then, we performed a few corrections and rescalings that we describe in the next paragraphs. More specifically, we made a correction to exclude OoT events (Section 4.1), and we rescaled the raw number of events $c_j$ (where $j$ corresponds to the $j$th CCD of the pn instrument) for the exposed area (Section 4.2), active time (Section 4.3), and energy band (Section 4.4).

For the MOS2 camera, we studied the unconcentrated background on a kilosecond timescale (Gastaldello et al. 2017). This is not possible for the pn camera, since the exclusion of the time periods in which the inFOV background is high leads to a much lower statistics. We shall therefore combine the time periods in which the inFOV background is high leads to a much lower statistics. We shall therefore combine the time periods in which the inFOV background is high and the presence of SEPs or proton flares (light red).

4.1. OoT Events Evaluation

Events registered during readout (OoT events) are assigned an incorrect positioning along the readout column. This results in a contamination in the outFOV area due to inFOV OoT events. In the following paragraphs, we will describe the method we used to evaluate this component.

The task eproc offers the possibility to simulate OoT events based on the original event list. By rerunning the task, it is possible to create an event list that treats all events as OoT events; the Y chip coordinate (RAWY) is simulated by randomly shifting the events along the RAWY axis. We extract events $e_{OoT}^{j,raw}$ from this list using the same prescriptions as in Section 3.2. The number of resulting events must be multiplied for the ratio of the readout and integration time ($T_R/T_I = 0.063$ for full-frame mode exposures and 0.023 for extended full-frame mode). The current implementation of epevents (called the eproc task) does not automatically detect the instrument and bad pixel setting; thus, a rescale of about 95% must be applied manually. This is repeated for each jth CCD (where $j$ runs from 1 to 12).

Therefore, the number of OoT events expected in the outFOV area is

$$c_j^{OoT} = c_j^{OoT} \frac{T_R}{T_I} \times 0.95. \tag{1}$$

4.2. Area Rescale

Standard SAS tools do not allow for exposure map creation outside the FOV. In order to rescale the counts detected from the outFOV area to the inFOV area, we relied on an outFOV cheesed mask, $M_{out}$. It is produced following the outFOV definition reported in Section 3.2 and covers 2.512 cm$^2$ (corresponding to 52.780 arcmin$^2$), and the size of its pixels is 1″. For each jth CCD, we define $N_{j,out}$ as the number of pixels having a value equal to 1 in $M_{out}$ in the jth CCD. For each CCD, the area rescale factor $R_j$, measured in cm$^{-2}$, is defined as

$$R_j = \frac{N_{j,out}}{2.512}. \tag{2}$$

4.3. Good Time Computation

For each CCD, we need to know the time in which the pn was taking events. To compute the observing time for a single exposure and the jth CCD, $T_j$, we must take into account different effects: the nominal good time intervals (GTIs), the excluded on-flare time periods, and the losses of exposure time.

The GTI extension of the event file provides the nominal lists $L_{i,GTI}$ of time periods in which each CCD is operating correctly. These nominal lists of GTIs must be excised of on-flare periods. Following the analysis reported in Appendix A, we derived the list $L_{out}$ of on-flares of each observation. By removing these intervals from each $L_{i,GTI}$, we get the lists of GTIs of off-flare periods $L_{i,off}$ for each CCD.

Discarded CCD columns and rejection of MIPs are registered as losses of exposure times. Such losses of exposure times (together with the dead-time computation) are accounted for by

\[ \text{https://xmm-tools.cosmos.esa.int/external/sas/current/doc/epchain/index.html} \]
renormalizing the nominal frame time $T_f$ of each time frame through the FRACEXP column in the EXPOSU extension of the event file, which provides the fractional exposure, $f_i$, of each time frame $i$. The effective observing exposure of each time frame $i$ is $T_{i}^{\text{eff}} = T_f \times f_i$. The total good time $T_g$ for each CCD is the sum of the effective exposures on all of the $n$th time frames in the CCD $L_{j,\text{off}}$ list:

$$T_g = \sum_{i=1}^{n} T_{i}^{\text{eff}}.$$  (3)

4.4. Time-series Computation

For each exposure and revolution, we computed the surface brightness $s_b$ in the outFOV region, measured in the 10–14 keV energy band as

$$s_b = \frac{1}{\Delta E} \sum_{j=1}^{12} \frac{c_j - c_{j,\text{OoT}}}{T_j R_j}, \quad \sigma_{s_b} = \frac{1}{\Delta E} \sqrt{\sum_{j=1}^{12} \frac{c_j + c_{j,\text{OoT}}}{T_j^2 R_j^2}},$$  (4)

where $c_j$ (Section 4) is the number of observed counts, $c_{j,\text{OoT}}$ (Section 4.1) is the predicted number of OoT counts, $R_j$ (Section 4.2) is the area rescale factor, $T_j$ (Section 4.3) is the total good time, and $\Delta E = 4$ keV is the energy bandwidth.

The surface brightness time series by exposure and revolution are reported in Figure 3. Using Equation (4) to evaluate the surface brightness of our entire sample, we obtain $s_{b,\text{sample}} = (5.118 \pm 0.003) \times 10^{-3}$ counts s$^{-1}$ cm$^{-2}$ keV$^{-1}$.

4.5. Outliers

From the mean (Figure 4), it is apparent that the tails of the distribution of deviations are highly asymmetric; there are 28 outlier exposures (over 3104, about 0.9%) that show an excess $>4\sigma$ (marked in red in the left panel of Figure 3), while no exposure deviates at more than $-4\sigma$. This cannot be due to a statistical effect; thus, we expect that these “excesses” contain some form of contamination. To investigate this issue, we inspected the EXTraS and radiation monitor$^{12}$ light curves and the pn images of these exposures.

We noticed that in 18 of the 28 observations, the off-flare exposure time was lower than 3 ks. We suspect that these exposures are entirely contaminated by SP flares. Under such circumstances, the cleaning procedure described in Appendix A can incorrectly assume that the four bins with the lowest count rate are flare-free.

Furthermore, in 12 of the 28 exposures, the radiation monitor light curve suggests the presence of low residual levels of SEPs not recognized by the ESA Solar Energetic Particle Environment Modeling application server (see, e.g., Figure 5 from Gastaldello et al. 2017). Since we excluded SEP periods, these exposures should be excluded from our sample.

Finally, in seven of the 28 exposures, we found hard, bright sources falling on the edge of the FOV. Thus, we cannot exclude photon contamination of the outFOV coming from such sources.

Since it is apparent that the selected exposures have an outFOV highly contaminated by protons, contaminated by photons and/or fall during SEP periods, we will conservatively mark them as outliers. They will be treated separately (where possible, otherwise excluded) in the following analysis. We shall make a posteriori considerations of these outliers in Section 5.2.

After the removal of the 28 excesses, we repeated the computation of $s_b$ as in Equation (4) for each revolution.

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12 https://www.cosmos.esa.int/web/xmm-newton/radmon-details
revealed three revolutions instead of for each exposure. Again, a running mean analysis revealed deviations larger than ±4σ (marked in red in the right panel of Figure 3); these will be treated separately (where possible, otherwise excluded) in the following analysis.

### 5. Time Series: Results

#### 5.1. Analysis of Different Optical Filters and Submodes

In order to test whether different observation settings—such as the choice of the optical filter or observing submode—can change the outFOV surface brightness, we will analyze the time series of outFOV sb separating exposures performed with different optical filters and submodes.

Each EPIC camera is equipped with a set of three separate optical filters, named thick, medium, and thin. Although these filters absorb part of the incoming focused events (from both photons and SPs), they are almost transparent to high-energy particles and therefore sb should not depend on the filter used. Figure 5 (upper-left panel) reports the outFOV surface brightness as a function of time for different optical filters. The three samples of surface brightness appear to be consistent.

In order to statistically test the differences among these distributions, we must consider that they have a different occurrence; e.g., the thick filter was used more often during the first years of operation. This, coupled with the variation of the surface brightness with time, requires a binning (on the exposure-based data set) to perform most of the statistical tests. In analogy with the algorithm used to estimate the outlier exposures and revolutions (Section 4.5), we compared the deviations between the surface brightness for a given filter against the running mean calculated on the four nearby data points with a different filter. As we did in Figure 4, we built histograms (one for each filter) of such deviations, then we normalized for the total number of exposures and plotted a Gaussian model (see Figure 5, lower-left panel). A difference in the overall population would result in a difference in the distributions. We found that the parameters are consistent within 1σ (see Table 1).

We tried a different approach, binning the exposures in time with a step of 1 month, and we tested the three binned distributions. We performed both a Kolmogorov–Smirnov test using the binned surface brightness and a multidimensional Kolmogorov–Smirnov test using both time and surface brightness on each pair of the three distributions (Peacock 1983; Fasano & Franceschini 1987; Press et al. 1992). The three distributions are consistent within 5σ.

As a further test, we plotted the binned sbthin, sbmedium, and sbthick obtained with the 1 month step in pairs; for each pair, the points are best fitted by a linear distribution compatible, within 3σ, with a 1:1 relation.

We also tested for differences associated with the two different submodes, full frame and extended full frame, which differ for time resolution (73.4 and 199.1 ms, respectively) and the ratio of integration and readout time (6.3% and 2.3%, respectively), leading to a different percentage of OoT events. If OoT events are treated correctly, we do not expect any difference between the two samples of exposures. The two samples are shown in Figure 5 (upper-right panel). We followed the same procedure as before to group and test the two distributions. Again, the two distributions are consistent using the running mean method (within 1σ, lower-right panel) and the Kolmogorov–Smirnov tests (within 5σ), and the linear fit of sbFF versus sbEFF is compatible (within 3σ) with a 1:1 relation.

We thus found no variation of the outFOV surface brightness that we extracted either with the submode or with the optical filter used. While the first result is useful only as a test of the method we used, the latter result provides an important clue about the particles responsible for the outFOV count rate. This will be discussed in Section 7.
5.2. pn–MOS2 Comparison

The pn camera is composed of 12 back-illuminated pn CCDs, while the MOS cameras are composed of seven EEV type 22 front-illuminated CCDs. They differ in sensitivity thickness, quantum efficiency, and energy response (see, e.g., Strüder et al. 2001; Turner et al. 2001). A comparison among pn and MOS cameras thus offers a unique opportunity to analyze the sensitivity to the unconcentrated background of different X-ray detectors that share the same particle environment.

To perform this, we rely on the data set of MOS2 outFOV count rates reported in Marelli et al. (2017). Since we do not have an analogous data set for the MOS1 camera (see also the discussion in Marelli et al. 2017), we restrict our comparison to MOS2. From the starting MOS2 data set, we excluded time periods at the beginning and end of each orbit (orbital phase <0.15 or >0.8), since the outFOV is possibly contaminated by

Figure 5. Upper panels: surface brightness extracted from the outFOV area of the pn (Section 4.4) against time for individual exposures and computed from Equation (4). In the left panel, exposures taken with the thin optical filter are marked in black, with the medium optical filter in red and the thick optical filter in blue. In the right panel, exposures taken with the full-frame submode are marked in black and extended full-frame submode in red. Lower panels: histograms of deviations, in $\sigma$, of the sb value computed for each exposure of a given filter/mode from the result of the running mean analysis performed on the other filters/modes (Section 5.1) and the best-fitting Gaussian. Colors are the same as in the upper panels.
We report the value of the maximum, maximum position, and the intrinsic scatter of each Gaussian.

The intrinsic scatter on the y-axis is \( \sigma_{\text{intrinsic}} = 1.17 \times 10^{-4} \) counts s\(^{-1}\) cm\(^{-2}\) keV\(^{-1}\) (2.3% of the surface brightness evaluated over our entire sample, \( \sigma_{\text{sample}} \)); see Section 4.4.

Although the 28 outlier pn exposures (Section 4.5) have not been fitted, they do not significantly change the results of the fit. They are mostly above the fitted relation; the presence of an excess of counts in the pn outFOV undetected by MOS2 confirms that these exposures are exceptionally contaminated in the pn camera, probably due to SPs and photons.

### Table 1

| Filter/Mode | Maximum | Maximum Position | \( \sigma \) |
|-------------|---------|------------------|--------------|
| FF          | 0.167 ± 0.006 | -0.03 ± 0.03 | 1.18 ± 0.02 |
| EFF         | 0.165 ± 0.007 | 0.02 ± 0.04 | 1.18 ± 0.03 |
| Thin        | 0.172 ± 0.006 | -0.02 ± 0.03 | 1.14 ± 0.03 |
| Medium      | 0.172 ± 0.005 | 0.05 ± 0.03 | 1.15 ± 0.02 |
| Thick       | 0.161 ± 0.012 | -0.08 ± 0.08 | 1.16 ± 0.06 |

Note. We report the value of the maximum, maximum position, and \( \sigma \) of each Gaussian.

### 6. Imaging

To study the spatial distribution of the unconverted background in the outFOV area, we produced the total count map \( C_{\text{out}} \) by summing the images of all exposures in our data set and with our event selection. All images are in detector coordinates and have a pixel size of \( 1'' \). Similarly to \( C_{\text{out}} \), we created the total OOT count map \( c_{\text{out}} \), corrected as in Section 4.1. We produced the total exposure map \( T \) by evaluating, for each pixel in the outFOV area, the exposure time following Equation (3). Figure 7 (left panel) reports the surface brightness map, defined as \( (C_{\text{out}} - c_{\text{out}})/T \). A first inspection of the surface brightness map does not reveal any spatial dependence of the unconverted background. As a further test, we analyzed the radial surface brightness profile.

The radial profile could be affected by systematic effects induced by pixelization. Indeed, the event selection described in Section 3.2 was performed with SAS expressions (in principle, without any pixelization), while we applied an area rescale based on the \( 1'' \) pixel mask \( M_{\text{out}} \) (Section 4.2). This effect causes an artificial lower count rate at the borders of the mask and/or some counts falling just outside the mask borders. We estimate that this effect causes a count-rate loss that artificially lowers the sb from Equation (4) of \( \sim 0.2\% \) (evaluated over the entire data set). This is about an order of magnitude smaller than the intrinsic scatter on the relations reported in Section 5.2 and therefore negligible. Surface brightness profiles would instead be distorted, since this effect is located on the border pixels. For the imaging analysis, we shall therefore exclude the border pixels.

In order to produce a radial brightness profile, we used annuli centered on the geometrical center of the pn camera with width \( v = 5'' \). For each annulus centered at radius \( r \), we extracted the area-corrected observed counts as \( c(r) = \sum_{i=1}^{n} C_{\text{out},i} M_{\text{out},i} \), where \( i \) is an image pixel over the \( n \) pixel within the annulus, and \( M_{\text{out},i} \) is a mask modified to exclude border pixels. Similarly, we extracted the area-corrected OOT counts \( c_{\text{OOT}}(r) \) as in Section 4.1. For each annulus, we extracted the exposure time as \( t(r) = \sum_{i=1}^{n} T_{\text{out},i} \). We introduced a conversion factor on the area to convert from square pixels (where 1 pixel = \( 1'' \)) to square centimeters: \( f_{A} = 1.322 \times 10^2 \text{cm}^2 \text{pixel}^{-2} \).

We built the surface brightness radial profile using, for each annulus,

\[
\text{sb}(r) = \frac{c(r) - c_{\text{OOT}}(r)}{t(r)f_{A}}.
\]

The resulting surface brightness profile is reported in the right panel of Figure 7.

The radial surface brightness profile in the outFOV region features a very modest but statistically significant decline; a fit with a constant model results in a null hypothesis probability of \( 3.1 \times 10^{-4} \). A small excess is present in the inner region of the outFOV, likely associated with residual contaminants.
Appendix B

The model composed of a Lorentzian function plus a constant maximum of the Lorentzian to the best-model to our data does not depend on the intensity of the input coordinates.

During SP cleaning, we extracted the surface brightness of each quadrant. Quadrants 2 and 3 have a surface brightness that is significantly higher than that of quadrants 1 and 4. We conclude that the unconcentrated background from the corner data is to measure the unconcentrated background from the outFOV region.

To evaluate the spatial distribution of counts within the outFOV, we extracted the surface brightness of each quadrant. We found that quadrants 2 and 3 (the rightmost quadrants in detector coordinates) are in agreement within 1σ, as are quadrants 1 and 4. Quadrants 2 and 3 have a surface brightness that is significantly higher than that of quadrants 1 and 4. We conclude that the unconcentrated background extracted from the outFOV region in the 10–14 keV energy band does not show spatial variations higher than 2%.

7. Discussion

We have presented clear and incontrovertible evidence that corners of the pn detector are exposed to photons and particles concentrated by the X-ray telescope (see Section 2). This contamination features a radial profile, well modeled by a quasi-Lorentzian function, that varies in intensity but not shape (see Appendix B). It covers the entire outFOV and thus prevents us from directly using the corner data to measure the unconcentrated particle background, as done for the MOS. We therefore devised a modified approach to assess this component, consisting of first cleaning the corner data from photon and proton contamination as well as possible and then measuring the background rate from the outFOV area.

The validity of this method is confirmed by the analysis of the radial brightness profile of our entire sample (Section 6), which revealed a total residual contamination of less than 1% of the total surface brightness. Moreover, the low scatter in the relation between the outFOV surface brightness of the pn and MOS2, with the latter unaffected by this contamination, has shown that the difference in the level of contamination between different revolutions is low. Indeed, this must be included in the intrinsic scatter in the pn-versus-MOS2 correlation—2.3% of the surface brightness evaluated over our sample, sb_*sample.* This can be adopted as an upper limit to any difference in contamination between different revolutions.

Having devised for the first time a technique to use pn corner data to monitor the unconcentrated particle background, we now go on to discuss (1) the effective proxies of the pn background and (2) the implications for the nature of the pn particle background.

7.1. Proxies of the pn Background

To evaluate the unconcentrated background in the inFOV, the first possibility is to use the corner data of the pn. As shown in Section 2 and Appendix B, the presence of substantial contamination from concentrated SPs and photons is a clear limitation to this approach. The data need to be cleaned carefully for SP flares before a measure of the pn background from the corner can be made. Note that this method works less than perfectly on observations where SP-cleaned data are insufficient to allow a measurement. A large fraction of the outliers in Figures 3 and 4 are probably due to this effect. Finally, since concentrated photons contribute to the contamination of the outFOV region, such a method should be avoided in the case of bright, extended celestial sources detected in the inFOV.

A second possibility to evaluate the unconcentrated background in the inFOV is to measure the unconcentrated background from

Figure 6. Revolution-based surface brightness for the pn (sb; Section 5.2) vs. MOS2. The best-fitting linear relation obtained in Section 5.2 is shown in blue, with 1σ uncertainties in light blue. In the left panel, we report the revolution-based sb obtained by exceeding outlier exposures and revolution (as defined in Section 4.5). In the right panel, we show the revolutions that are outliers or contain outlier exposures in the pn camera distribution (in green). In red, we mark the only revolution that is an outlier for both the pn and MOS2. The dashed green line reports the best fit of these outlier points.
concentrated photons and SPs.

The difference between the integrals of the blue and red components, renormalized for the area, gives the contamination due to the best fit with a constant model plus a Lorentzian, shown in red and blue, respectively, with 1σ errors using the model in Equation (B1) (Appendix B) and prescriptions described in Section 6. The difference between the integrals of the blue and red components, renormalized for the area, gives the contamination due to concentrated photons and SPs.

Figure 7. Left panel: surface brightness map defined as in Section 6 for our entire sample, in detector coordinates and units of counts s\(^{-1}\) cm\(^{-2}\) keV\(^{-1}\). In cyan, we show the CCD borders and nearby excluded pixels. In black, we mark the area excluded from the outFOV definition. In green, we mark the area excluded for bad pixels and columns. Right panel: surface brightness profile from the geometrical center of the pn detector with a 5\(^{th}\) step, computed following Equation (6). We report the best fit with a constant model plus a Lorentzian, shown in red and blue, respectively, with 1σ errors using the model in Equation (B1) (Appendix B) and prescriptions described in Section 6. The difference between the integrals of the blue and red components, renormalized for the area, gives the contamination due to concentrated photons and SPs.

MOS2 corner data, following the method described in Marelli et al. (2017), and estimate the pn unconcentrated background in the outFOV from the relationship between MOS2 and the pn presented in Section 5.2. The resulting pn surface brightness should take into account a systematic error of 1.17 × 10\(^{-2}\) counts s\(^{-1}\) cm\(^{-2}\) keV\(^{-1}\), which reflects the intrinsic scatter in the MOS2/pn relation. This surface brightness can be extended to the entire pn energy band using the unconcentrated background spectral modeling derived from closed data or blank sky fields (see, e.g., Freyberg et al. 2004; Katayama et al. 2004; Fraser et al. 2014).

This option has the advantage that no SP flare cleaning needs to be performed, since the MOS2 corners are properly shielded from the sky. It also affords better statistics and temporal coverage than what is available through the pn corner data. As discussed in Section 5.2, the nonsimultaneity between the MOS2 and pn measurements, as well as any other effect, induces systematic errors that are contained within the 2.3% intrinsic scatter measured in the MOS2-versus-pn correlation.

A third alternative, which has not been explored in this paper, consists of the use of pn “discarded lines.” A column is discarded when an event above the upper limit threshold is detected; this procedure is called MIP rejection. Since the vast majority of the MIP events are particle events, the number of discarded columns is closely related to the unfocused background count rate. This option has been investigated in the past within the EPIC pn team (see, e.g., Freyberg et al. 2004; Katayama et al. 2004) and more recently by the SOC using NDSLIN in EPIC pn as a proxy for the quiescent particle background (I. de la Calle, XMM-Newton SOC, 2019\(^{14}\)).

7.2. Origin of the pn Unconcentrated Background

In this section, we investigate the origin of the pn background. To this aim, we introduce a set of measurements of high-energy protons collected with the EPHIN detector on board SOHO; see Kühl et al. (2016) for details.

In Figure 8 (left panel), we show a time series (on a month timescale) for high-energy protons in the range 630–970 MeV accumulated with EPHIN. To ease comparison between the two time series, we normalized them by setting their integrals equal to 1. Similarly, we produced the time series of pn corners on a month timescale using Equation (4). Comparison of the EPHIN and pn time series reveals a striking similarity between the two. To investigate further, we correlated the EPHIN and pn time series, finding a remarkably tight relationship between the two; see Figure 8 (right panel). A linear fit shows that, barring a few outliers, quite likely originating from the pn (see, e.g., Section 4.5), the vast majority of data points are clustered very tightly around the best-fitting line. To evaluate this, we do not rely on the intrinsic scatter, as in Section 5.2, since it assumes that errors are statistical in nature and, in the case of EPHIN data, the systematic errors are important (see Section 3 of Kühl et al. 2016). We shall instead use the total scatter on the y-axis, defined as

\[
s_t = \sqrt{\frac{\sum_{i=1}^{N} (y_i - \bar{y}(x_i))^2}{N}},
\]

where \((x_i, y_i)\) are the \(N\) fitted points (including the aforementioned outliers), and \(s_t\) is \(1.66 \times 10^{-4}\) counts s\(^{-1}\) cm\(^{-2}\) keV\(^{-1}\), namely, 3.5% of the median of the pn monthly renormalized rate. Note that the total scatter includes the intrinsic scatter and

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\(^{14}\) Available at https://www.cosmos.esa.int/web/xmm-newton/background.
can be regarded as an upper limit for the latter. This comparison strongly suggests that cosmic-ray protons are one of the main contributors to the unconcentrated pn background.

The lack of any detectable differences between unconcentrated background rate measures with different pn filters and submodes (see Section 5) is consistent with this interpretation. Indeed, as shown by simulations carried out on instruments similar to the pn (von Kienlin et al. 2018), the unconcentrated background associated with high-energy protons is traced back to secondaries, mostly electrons and photons, produced in the immediate vicinity of the detector, and there is no reason to assume that either filters or submodes affect these processes.

Although the EPHIN and pn time series bear a striking resemblance, they also differ in one important respect: the maximum-to-minimum ratio for the EPHIN curve is significantly larger than for the pn (see Figure 8). When performing a linear fit to the correlation between the two quantities, such a difference manifests itself as a nonzero constant term. This is indeed what is found; the pn surface brightness extrapolated to a zero EPHIN rate is $s_{0} = (2.07 \pm 0.06) \times 10^{-3}$ counts s$^{-1}$ cm$^{-2}$ keV$^{-1}$, $\sim 30\%$ to $\sim 70\%$ of the revolution-based surface brightnesses. The most obvious interpretation of this result is that there is some other agent contributing to the pn background beyond cosmic-ray protons. Whatever the nature of this component, it must vary little or not at all over the solar cycle. Indeed, any variation uncorrelated with the solar cycle would lead to a scatter in the EPHIN-versus-pn relation. Thus, the total scatter $s_{c}$ can be used to set an 8% upper limit on any variation of $s_{0}$. The question we ask ourselves is: what could be responsible for this component? Following standard scientific practice, we shall start by investigating the eventuality that it is some artifact in the data. A possibility that we can quickly rule out is the existence of some spurious correlation between the EPHIN and pn data sets; the measures were extracted from detectors located $\sim 1.5 \times 10^{9}$ km apart and reduced and analyzed independently of each other. Another possibility is calibration. Kühl et al. (2016) estimated a calibration uncertainty of about 20% on EPHIN data; this uncertainty could be related to the absolute or relative calibration. If it is related to the absolute calibration, then it has no impact on the constant term in the linear relation. Indeed, if the EPHIN fluxes were all systematically off by a certain percentage (of the fluxes themselves), it would lead to a change in the slope of the correlation, not on the constant term (since the zero-point of the EPHIN flux does not change). Conversely, if the issue were on the relative calibration, i.e., if the values of single points were offset with respect to other data points in the EPHIN time series, we would observe a scatter in the relation with the pn detector. Since the scatter in the relation is small, this implies that any relative calibration issue must also be small, less than $1.52 \times 10^{-2}$ counts s$^{-1}$ sr$^{-1}$ GeV$^{-1}$, that is, 6% of the median on the EPHIN monthly fluxes. This is estimated from the best-fit parameters and associated uncertainties. Note that this argument can be turned around and applied to the pn data with similar results; any relative calibration uncertainty on pn fluxes must be contained within 3.5% of the pn surface brightness evaluated over our entire sample, $s_{\text{sample}}$.

7.2.1. The Constant Component

Having found no evidence that the constant term is an artifact, we proceed with an evaluation of any systematic error that might be affecting it. Before reaching the pn detector, cosmic-ray protons must travel through a significant amount of matter, roughly 3 cm of equivalent Al (Hall et al. 2007). Under such conditions, lower-energy protons, which are of course more copious, stand a lower chance of traversing the shielding without being absorbed than higher-energy protons. The net effect is that the protons responsible for the pn background

Figure 8. Left panel: $s_{\text{pn}}$ (counts s$^{-1}$ cm$^{-2}$ keV$^{-1}$; black) and EPHIN flux (0.6–1 GeV band, counts s$^{-1}$ cm$^{-2}$ sr$^{-1}$ GeV$^{-1}$; red) vs. time. We normalized the $s_{\text{pn}}$ and EPHIN flux to ease comparison between the two time series. The EPHIN error bars take into account both statistical and systematic error (see Section 3 of Kühl et al. 2016) Right panel: $s_{\text{pn}}$ vs. EPHIN flux (0.6–1 GeV band). The best-fit relation, with 1σ errors and fitted using the same procedure as in Section 5.2, is shown in blue. It has the form $s_{\text{pn}} = m(F_{\text{EPHIN}} - F_{\text{null}}) + q$, where $s_{\text{pn}}$ is the pn surface brightness, $F_{\text{EPHIN}}$ is the EPHIN flux, $q = (4.47 \pm 0.01) \times 10^{-3}$ counts s$^{-1}$ cm$^{-2}$ keV$^{-1}$ is the constant term evaluated at the pivot point $F_{\text{null}} = 0.245$ counts s$^{-1}$ cm$^{-2}$ sr$^{-1}$ GeV$^{-1}$, and $m = (1.09 \pm 0.01) \times 10^{-2}$ (counts s$^{-1}$ cm$^{-2}$ keV$^{-1}$)/(counts s$^{-1}$ cm$^{-2}$ sr$^{-1}$ GeV$^{-1}$) is the slope; the relation intersects the y-axis ($F_{\text{EPHIN}}$ null) at $s_{\text{pn}} = 2.07 \pm 0.06 \times 10^{-3}$ counts s$^{-1}$ cm$^{-2}$ keV$^{-1}$.
have a broad distribution in initial energy, ranging from a few hundred MeV to several GeV. Since the solar modulation affecting cosmic-ray protons depends upon their energy, with the more energetic protons less modulated (see, e.g., Potgieter & Vos 2017), the modulation of the proton-induced pn background will result from a weighted mean of the modulation of cosmic-ray protons. If the distribution of matter around the pn detector were known rather precisely, we could compute an appropriately weighted EPHIN proton time series, correlate it with the pn time series, and derive a robust estimate of the constant term. Given our lack of detailed knowledge of the pn camera, we are forced to take a more conservative approach; we repeat our estimate of the constant term by correlating the pn data with EPHIN proton curves of sufficiently low and high energies to derive an upper and lower bound to the constant term. To this aim, we used the curves of 500 MeV and 1.2 GeV. We find that in the first case, the constant term is \( \sim 2.5 \times 10^{-3} \text{ counts s}^{-1} \text{ cm}^{-2} \text{ keV}^{-1} \), and in the latter case, it is \( \sim 1.3 \times 10^{-3} \text{ counts s}^{-1} \text{ cm}^{-2} \text{ keV}^{-1} \).

Having derived a robust estimate of the constant component, as we shall henceforth call it, we come to the question of its origin. A possibility we can discard rather quickly is that it comes from cosmic-ray electrons or alpha particles. Since both of these species follow a solar cycle modulation very similar to the one for protons, they cannot be responsible for a component that is consistent with being constant over the solar cycle.

Having established that our component is not related to the solar cycle and that it must be very close to being constant, we are left with a limited range of options. Particles of heliospheric origin have much softer spectra than cosmic rays, which means they cannot penetrate the shielding around the pn detector, with the possible exception of electrons, which have a much smaller cross section than protons and alpha particles. It is hard to accept the unlikely possibility that suprathermal electrons, that are known to vary by several orders of magnitude in flux, might yield a constant component.

Another possibility is that the constant component is produced through activation. Activation is the process in which cosmic rays, mostly neutrons, excite nuclei, which later return to their ground state by emitting gamma rays. Since radioactive nuclei can exhibit half-lives ranging from small fractions of a second to several weeks or even months, this process allows for emission of gamma rays a long time after the material has been activated. After a few weeks, or at most months, in orbit, activation should produce a roughly continuous contribution to background. There are two things suggesting that activation is not responsible for the bulk of the constant component: (1) the half-life for the vast majority of the excited nuclei is much shorter than the solar cycle, which implies that, even if with some delay, particle contribution due to activation should follow the solar cycle; and (2) the contribution is expected to be small; in a recent study of the WFI detector to be flown on ATHENA, which for the purpose at hand is very similar to the EPIC pn, it was shown that this process does not account for more than a few percent of the total background.

If not particles, perhaps photons could be the primaries we are seeking. We have direct evidence that photons in the range 50–200 keV can penetrate the shielding around the pn detector. On 2004 December 27, a giant flare from the soft gamma repeater SGR 1806–20 was recorded by several observatories (e.g., Hurley et al. 2005; Mereghetti et al. 2005). At precisely the same time, the EPIC pn and MOS detectors registered an increase in the background rate of more than an order of magnitude (Figure 9).

![Figure 9](image)

**Figure 9.** Light curve of the giant flare from SGR 1806–20, as seen by INTEGRAL/SPI (18 keV–8 MeV, time bin size 0.05 s, and the peak is saturated; Mereghetti et al. 2005) and XMM-Newton/pn (0.2–14 keV, time bin size 0.1 s). Time zero has been chosen following Mereghetti et al. (2005). Contemporaneous flares have also been registered by the MOS1 and MOS2 cameras, although their time resolution is worse (2.6 s). Flare events are registered throughout the entire pn detector (both inFOV and outFOV), and its spectrum is consistent with a power law with \( \Gamma \sim 0.2 \).

...
paper and may actually be hard to achieve given the limited documentation available for the EPIC cameras.

Our findings have profound implications for future X-ray experiments, particularly for the ATHENA WFI, which bears strong similarities to the EPIC pn. The tight correlation between EPHIN flux and pn background rate, as well as the detection of a secondary source of background events, most likely associated with cosmic X-ray photons, provides the first important validations of simulation studies performed by the ATHENA WFI Background Working Group (von Kienlin et al. 2018). Moreover, the correlation between EPHIN and pn strongly suggests that a high-energy particle monitor can contribute decisively to the reproducibility of the background for both experiments on ATHENA, i.e., WFI and XIFU.

8. Summary

We have analyzed the largest data set ever used for studies of the XMM-Newton EPIC/pn unconcentrated background. From the outFOV region of the detector, we collected 2.5 × 10⁶ events in the 10–14 keV energy band using a total exposure time of 53 Ms on 1353 revolutions spanning 12 yr (2000–2012). Our analysis produced the following results.

1. The region known as outFOV is in fact largely contaminated by concentrated photons and SPs. Focusing on the SP contamination, its surface brightness radial profile follows a quasi-Lorentzian distribution whose normalization is proportional to the intensity of inFOV SPs but constant in shape. The contamination from photons is consistent with having the same characteristics.

2. A carefully selection of energy bands and time periods allowed us to measure the uncorrected background in the pn outFOV. We (1) reduced the outFOV contamination of our total data set to less than 1% of sb\textsubscript{sample} (the surface brightness evaluated over our entire sample) and (2) limited the contamination of all of the considered revolutions but a few outliers to less than 2.3% (of sb\textsubscript{sample}).

3. The uncorrected background in the pn outFOV does not show significant spatial variations higher than ∼2% or any dependence with the submode or optical filters used; its time behavior is anticorrelated with the solar cycle. Its surface brightness varies from ∼3 × 10⁻³ to ∼7 × 10⁻³ counts s⁻¹ cm⁻² keV⁻¹ over the considered period; the surface brightness evaluated over the entire period is sb\textsubscript{sample} = (5.118 ± 0.003) × 10⁻³ counts s⁻¹ cm⁻² keV⁻¹.

4. We found a tight linear correlation between the pn and MOS2 outFOV surface brightness with an intrinsic scatter of 2.3% (of sb\textsubscript{sample}). This relationship permits the correct evaluation of the pn uncorrected background of each exposure on the basis of MOS2 data, avoiding the use of the contaminated outFOV region of the pn.

5. We found a tight linear correlation between the pn uncorrected background and proton flux in the 630–970 MeV energy band, as measured by the EPHIN instrument. The intrinsic scatter of this correlation is <3.5% (of the median of the pn values). This confirms that cosmic-ray protons are one of the main contributors to the pn uncorrected background, accounting for 30%–70% of it, depending on the time of observation during the solar cycle.

6. The nonzero constant term in the EPHIN–pn relation implies that there is another source contributing to the pn uncorrected background. This agent does not depend on the solar cycle or vary with time and is roughly isotropic. After having ruled out several candidates, we found that the hard X-ray photons of the CXB satisfy all known properties of this constant component.

7. Our findings have profound implications for ATHENA. The tight correlation between the EPHIN flux and pn background rate, as well as the detection of a secondary source of background events, provide the first important validations of simulation studies performed on ATHENA. Moreover, the correlation between EPHIN and pn strongly suggests that a high-energy particle monitor can contribute decisively to the reproducibility of the background of both experiments on ATHENA.

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Facilities: XMM, SOHO.

Software: astropy (Astropy Collaboration et al. 2013), numpy (Oliphant 2006), matplotlib (Hunter 2007), ltsfit (Cappellari et al. 2013), scipy (Virtanen et al. 2020), SAS (v 14.0 Gabriel et al. 2004).

Appendix A

Extraction of Off-flare Periods

We define the off-flare periods as the time intervals during which SPs do not significantly contaminate the pn detector. Therefore, they comprise time in which only the constant component of the background is present. To produce the GTIs of the off-flare periods, we rely on the inFOV light curves in the EXTraS database, which benefit from a better statistics than the light curve that we could obtain in the small outFOV region.

The EXTraS project (de Luca et al. 2016) carefully evaluated and subtracted, through complex modeling, pointlike sources to obtain 500 s time bin background light curves in the 0.2–12 keV energy band. Also, thanks to a better treatment of instrumental effects—such as the evaluation of CCD-dependent GTIs and the refinement of extraction regions—EXTraS light curves are better suited for background analysis than the standard results from SAS analysis.

Given the EXTraS inFOV background light curve as input, we implemented an algorithm to extract the off-flare periods. Before performing this analysis, we conservatively excluded all bins with a fractional exposure (the fractional CCD-weighted time of good exposure in the time bin) lower than 0.1 (thus, an

16 https://www88.lamp.le.ac.uk/extras/archive
The aim of our algorithm is to maximize the duration of the off-flare period, where the background light curve is consistent with a constant. This is equivalent to finding the highest possible constant value $c_{\text{off}}$ that fits the uncontaminated part of the light curve at a given confidence level. More specifically, we iteratively set a value of $c_{\text{off}}$ and exclude the time bins whose count rate $c_i$ shows the highest positive deviation $\delta_i = (c_i - c_{\text{off}})/\sigma_i$ ($\sigma_i$ being the statistical error on the count rate of the $i$th time bin). We iterate this procedure with lower and lower values of $c_{\text{off}}$ until all remaining bins are consistent with a constant at a given confidence level, parameterized by the input value $N_{\sigma}$ (see below). These time bins form the off-flare period. A few examples of light curves filtered with our algorithm are shown in Figure 10.

To obtain the best selection of off-flare periods, we have to wisely choose the confidence level used to check the consistency of the count rates with the constant, which is expressed by the input $N_{\sigma}$. To do that, we run our analysis using different values of $N_{\sigma}$, from 3 to 17. As an indicator of residual SP contamination in each exposure after filtering with a given $N_{\sigma}$, we use the scatter of the count rates around their weighted average. We then compare the mean of the scatters over all observations as a function of $N_{\sigma}$ in Figure 11. We chose $N_{\sigma} = 10$ as a reasonable compromise between contamination minimization and exposure time maximization.

Using our script, by construction, every curve has at least one off-flare time bin, even for exposures that are always contaminated by SP: the time bin with the lowest count rate in the light curve. Thus, we have to set a minimum number of good bins; below this value, the entire exposure is conservatively rejected. As for the choice of $N_{\sigma}$, the minimum number of bins of off-flare time is chosen as a compromise between contamination minimization and exposure time maximization. To estimate the contamination in the exposures as a function of the number of good bins, we divide them into subsamples based on the number of good bins. We then compute the median of the distributions of off-flare count rates for each subsample.18 In Figure 12, we show these values as a scatter of the number of registered events as a function of the fractional exposure for each bin. We verified that in each bin with a fractional exposure $>0.1$, we registered at least 30 counts (while this is not true if we use a lower limiting fractional exposure).

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{Figure10.png}
\caption{EXTraS background light curve (from inFOV, 0.2–12 keV) for a sample of pn exposures. The original curve in fits format, named as reported in each panel, can be found within the EXTraS archive. Green areas show the resulting off-flare time period for each exposure, as obtained by our script and using $N = 10$; $c_{\text{off}}$ is shown as a dashed blue line.}
\end{figure}
Figure 11. In blue, we show the percentage of exposure time as a function of the parameter $N_\sigma$ in our script. In red, we show the mean of the spread of each exposure (normalized for their weighted averages) for different values of $N_\sigma$. All of the parameters are evaluated over our main sample.

Figure 12. In blue, we show the percentage of off-flare exposure time as a function of the minimum off-flare bins per exposure. In red, we show the median of the count rates of the distributions of exposures with $N$ off-flare time bins as a function of $N$. All of the parameters are evaluated over our main sample.
function of the number of off-flare time bins per exposure. Since the contamination decreases quickly with the increasing number of off-flare bins and reaches a plateau around four, we chose to reject all exposures with less than four off-flare time bins. Moreover, to exclude low-statistic revolutions in our main data set, we shall only consider revolutions with at least 10 ks of off-flare time.

Appendix B
Modelization of OutFOV Contamination from SPs

Since SPs are the main source of contamination in the outFOV region for most of the XMM-Newton exposures, we want to study the radial dependence of the contamination and evaluate its impact in our main data set (Section 6). To do this, we decided to study the complementary contaminated data set (the “on-flare” time periods, the opposite of off-flare time periods defined in Appendix A), because it has more statistics than our clean data set, and to describe the radial dependence in the outFOV region with an empirical model that we then rescale to estimate the residual contamination in the clean data.

We made the same selection as in Section 3.1, but we kept only the complementary on-flare times. We chose to ignore periods with inFOV rates higher than 500 counts s\(^{-1}\) in order to minimize pileup effects.

Using the same event selection as in Section 3.2, we obtain a data set comprising 1.06 \(\times 10^7\) counts in the outFOV region (9 \(\times 10^6\) are expected to be OoT counts) over a 40.0 Ms exposure time. Using this huge data set, we built the radial surface brightness profile of the outFOV region during on-flare periods, following the same method reported in Section 6. In Figure 13, we report the surface brightness map and radial profile. The observed surface brightness during on-flare periods is maximum near the edge of the FOV and decreases steadily with increasing radius; the entire outFOV area is highly contaminated by SPs, as seen in Section 2 for small subsamples. We assume that the unconcentrated background has a flat brightness profile, while the profile variation is only due to the contamination. For both the MOS2 camera (Marelli et al. 2017) and the pn camera (Section 6), this is a fair assumption. We evaluated the surface brightness due to unconcentrated background during on-flare periods of our entire sample to be \(sb_{\text{onflare}} = 5.21 \times 10^{-3} \text{ counts s}^{-1} \text{ cm}^{-2} \text{ s}^{-1}\) using the surface brightness during off-flare periods of our entire sample (\(sb_{\text{sample}}\) from Section 4.4). We empirically found that the brightness profile in Figure 13 follows a Lorentzian model plus the constant \(b_{\text{onflare}}\), with a corrective factor depending only on the Lorentzian normalization,

\[
b(r) = N \frac{w^2}{(r - r_0)^2 + w^2} - 0.1158N + b_{\text{onflare}},
\]

where the width is \(w = (113''4 \pm 0''3)\) and the maximum is located at \(r_0 = (875''6 \pm 0''6)\) (from the geometrical center of the pn detector). Despite the huge number of events (\(~10^7\)), the fit is fully acceptable, with a null hypothesis probability (n.h.p.) of 0.13.

We checked the shape and/or parameters of the radial brightness profile for a dependence on (a) the intensity of SPs (counts s\(^{-1}\)), (b) time, or (c) angle.

(a) We divided our sample for different levels of flares to obtain 10 data sets with a similar statistics (\(~10^6\) counts). We built the brightness profiles of the outFOV region for each of them. Equation (B1) always provides a good fit (n.h.p. > 0.1),

![Figure 13](image.png)

*Figure 13.* Left panel: surface brightness map defined as in Section 6 for our on-flare sample, in detector coordinates and units of counts s\(^{-1}\) cm\(^{-2}\) keV\(^{-1}\). Right panel: surface brightness profile from the geometrical center of the pn detector with a 5'' step, computed following Equation (6), computed for our on-flare sample (\(~10^7\) counts). We used a step of 2''5. Effects related to OoT events, area, and time rescale are considered as described in Section 6. In red, we report the predicted off-flare brightness. In blue, we report the best fit described by Equation (B1).
All of the effects related to OoT events, area, and time rescale are considered as periods over our entire data set, divided by pn quadrant. We used a step of 2\degree.

Parameters of the Best Fits of the Brightness Profiles of the outFOV Region during On-flare Periods over Our Entire Data Set, Divided by pn Quadrant

| Quad. | n.h.p | N (10^{-2} counts s^{-1} cm^{-2} keV^{-1}) | w (arcsec) | r_0 (arcsec) |
|-------|-------|-----------------------------------|------------|------------|
| 1     | 0.026 | 4.90 ± 0.05                       | 117.4 ± 0.7 | 868 ± 2    |
| 2     | 0.211 | 4.55 ± 0.03                       | 112.2 ± 0.5 | 875 ± 1    |
| 3     | 0.049 | 3.80 ± 0.03                       | 108.0 ± 0.6 | 885 ± 1    |
| 4     | 0.989 | 4.23 ± 0.03                       | 116.3 ± 0.5 | 871 ± 1    |

Note. The model is reported in Equation (B1).

where the width w and maximum r_0 are always compatible within 2\sigma with the ones obtained for the entire sample. The only variable parameter is the normalization N, which increases proportionally to the inFOV flare rate.

(b) We divided our sample into 12 subsamples, one for each year of observation. Again, Equation (B1) fits all of the profiles well, and we have no evidence of variation of w and r_0.

(c) We extracted and separately fitted the radial brightness profiles of the four quadrants (corners) of the pn. Although the fit is still good for each of them (n.h.p. > 0.02), we find significant differences in the four best-fit sets of parameters (>5\sigma). The obtained radial brightness profiles and best fits are reported in Figure 14 and Table 2. The normalization N is maximum in the quadrant nearest to the boresight position and then decreases with the distance from it. This seems to point to a dependence of the contamination on the boresight position and/or proton vignetting.

We conclude that in the 10–14 keV band, the surface brightness profile of the contamination due to SPS in the pn outFOV region follows the empirical Equation (B1), where only the normalization N varies, with increasing with the inFOV flare rate. The contamination is slightly angular-dependent, but it always follows the empirical distribution of Equation (B1).

We note that the radial brightness profile of exposures highly contaminated by photons ("photon sample" in Section 2) is compatible with the same equation, although we rely on a much lower statistics (∼10^3 counts).

### Appendix C

#### SAS Event Selection

We report here the event selection from Section 3.2 in SAS notation.

We define the outFOV area as ((FLAG & 0x10000)!=0) & & !((DETY,DETX) IN circle(-2203.00,-1107.00, 18101.00)) & & !(DETY <= -16587) & & !(DETY in [-1227:-987]) & & !(DETY >=14373) & & !(DETX <= -18243) & & !(DETX in [-13143:-12843]) & & !(DETX in [-7763:-7443]) & & !(DETX in [-2363:-2043]) & & !(DETX in [3037:3337]) & & !(DETX in [8417:8737]) & & !(DETX >=13817).

We make use of the following pattern and flag selection:

(PATTERN <=4) & & !(FLAG & 0x1)==0 & & !(FLAG & 0x20)==0 & & !(FLAG & 0x40)==0 & & !(FLAG & 0x100)==0 & & !(FLAG & 0x20000)==0 & & !(FLAG & 0x80000)==0 & & !(FLAG & 0x800000)==0 & & !(FLAG & 0x400000)==0 & & !(FLAG & 0x8000000)==0.

We make use of the following energy selection:

(PI in [10000:14000]).

We excluded the following bright pixels and columns:

(!((DETX,DETY) IN circle(12957.0,11375.5, 201.0) || (DETY,DETX) IN circle(11004.5,12943.0,201.0) || (DETX,DETY) IN circle(-14953.0, 12423.0,201.0) || (DETY,DETX) IN box(7677,6753, 121,7781,0)).

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