‘PATCHING’ EPIC–MOS: TEMPORAL AND SPATIAL DEPENDENCY OF THE DETECTOR RESPONSE

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ABSTRACT

XMM-Newton, having now completed over 1000 revolutions of the Earth has been an outstanding success. The EPIC-MOS CCD X-ray detectors, comprising two of the three focal plane instruments on XMM-Newton, have observed many thousands of X-ray sources, and have collected close to a billion X-ray photons. This radiation has altered the behaviour of the MOS detectors in very interesting and subtle ways, and these changes and their evolution, and their effects on observations of cosmic X-ray sources are described here in detail. Furthermore, our methods and solutions to counter these effects through analysis and software are also presented.

Key words: X-rays; detectors; CCDs.

1. INTRODUCTION – THE PROBLEM

The EPIC focal plane spectrometers on *XMM-Newton* use CCDs to record the images and spectra of celestial X-ray sources focused by the three X-ray mirrors. There is one camera at the focus of each mirror, and two of the cameras (hereafter, MOS1 & MOS2) contain seven MOS CCDs, each combining high-quality imaging with near-Fano-limit spectral resolution (Turner et al. 2001).

Throughout the lifetime of the *XMM-Newton* mission, a thorough and detailed programme of instrumental calibration has been ongoing. Over the years, within the analysis of celestial X-ray source spectra, a curious phenomenon at the very lowest energies has been observed in the MOS detectors, and this effect can be seen by referring to Fig.1. Here, two MOS2 spectra are shown of the isolated neutron star RX J0720.4-3125 from both early in the mission (revolution 175) and from later in the mission (revolution 622). In both cases, the open (≈no attenuation) filter was used. This source was believed to be a constant flux point source [1], and thus the observed change in the spectrum was deemed due to instrumental effects. A similar, though not identical change is also seen in the MOS1 spectra. Once we were able to exclude many instrumental effects, including PSF, filter transmission and quantum efficiency changes, then it became clear that there was some intrinsic change in the redistribution properties of the CCDs of both MOS cameras, manifesting itself as a shift in the spectrum to lower energies, the effect being most pronounced at lower energies (below ~ 0.5keV). This effect was seen in many bright soft sources (e.g. Zeta Puppis, Revs 156 & 542), though curiously, as we shall see, not in all observations.

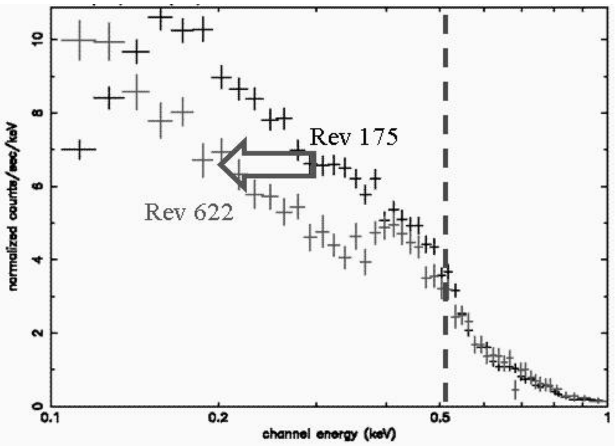

Figure 1. MOS2 spectra of the isolated neutron star RX J0720.4-3125 from revolution 175 (black) and from revolution 622 (grey). A shift in spectrum to lower energies is clearly seen.

2. OBSERVATIONS OF 1ES0102-72 AND ‘THE PATCH’

The various observations of the supernova remnant 1ES0102-72 proved invaluable in helping to solve the puzzle. We can be extremely confident that this remnant, being an evolved and resolved (angular diameter $\sim$1 arcminute) source, is a constant source in terms of flux and spectrum. Prior to revolution 850, 10 MOS1 and

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[1] As it turns out, this source is now not believed to be a truly constant source; small flux variations (far smaller than would account for the observed changes) are believed to have been seen.

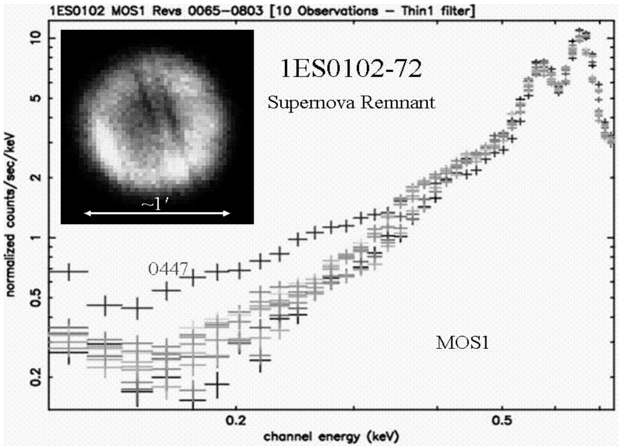

Figure 2. 10 MOS1 spectra of the SNR 1ES0102-72 from Revs. 65−803. One observation (from Rev. 447) clearly stands out as showing a shift in spectrum to lower energies.

11 MOS2 observations had be made of 1ES0102-72, all in the same mode (‘Large Window’) and with the same filter (thin). (The ‘missing’ MOS1 observation was performed in timing mode). In analysing all the spectra in a thorough and self-consistent way, we saw that all the low-energy spectra appeared the same, as expected, except for one MOS1 observation (Rev. 447), and for two MOS2 observations (Revs. 433 & 447), where the same shift in spectrum to lower energies was observed (The MOS1 case is shown in Fig.2). (Note that the MOS1 observation from Rev. 433 is the ‘missing’ timing mode observation.). One can see from Fig.2 that the spectrum shift here manifests itself as an increase in flux below 0.35 keV, together with a slight decrease in flux in the 0.35−0.55 keV range − i.e. an energy redistribution effect.

In forming images of the remnant in this very lowest energy band (0.1−0.35 keV), we were able to see (Fig.3) that both the MOS1 and MOS2 images from the ‘good’ observations looked markedly different from the corresponding images from the ‘bad’ observations − the ‘bad’ observations show a low-energy enhancement, or *patch* covering approximately one-half of the remnant.

It was therefore implicit in this that the enhancements seen in the Rev. 447 spectra were related to the ‘patches’ seen in the images, and to test this, spectra were extracted from the ‘on-patch’ and ‘off-patch’ regions of the remnant in the Rev. 447 observation, and from the corresponding remnant regions in the other observations, as delineated by the lines in Fig.3. Spectra from a ‘good’ observation, and from Rev. 447 are shown in Fig.4. It can be clearly seen that the spectral enhancement at low energies and the small deficit at slightly higher energies are due to the ‘patch’ visible in the images.

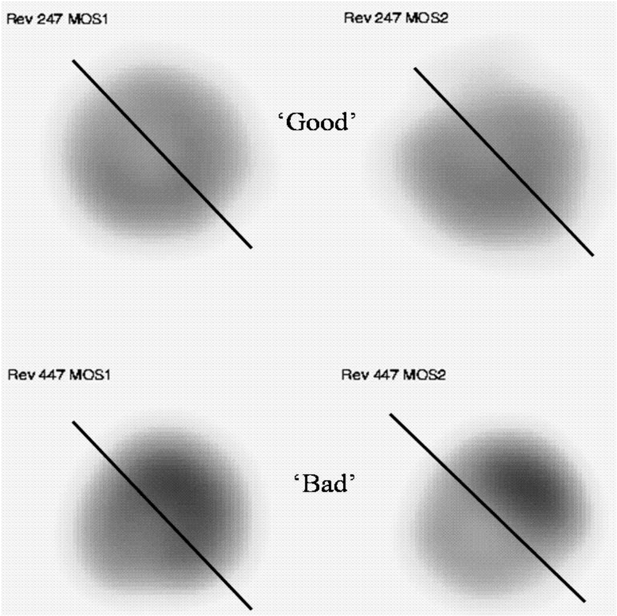

Figure 3. Low-energy (0.1−0.35 keV) smoothed MOS1 and MOS2 images of 1ES0102-72 from a ‘good’ observation (Rev. 247) and a ‘bad’ observation (Rev. 447). The ‘bad’ observations show a low-energy ‘patch’ over one-half of the remnant.

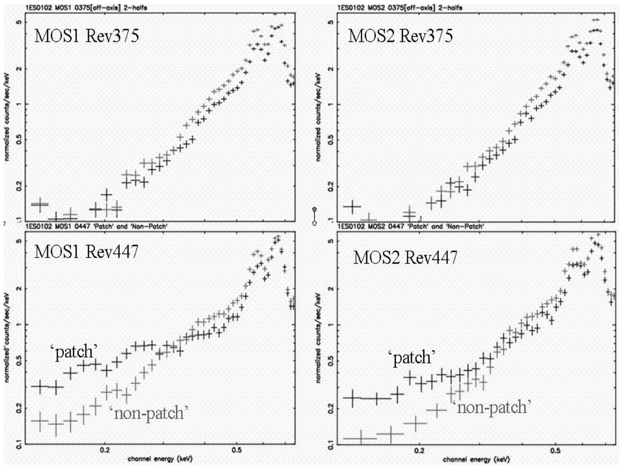

Figure 4. MOS1 and MOS2 spectra extracted from the two halves (black: ‘patch’, grey: ‘non-patch’) of 1ES0102: (top) for a ‘good’ observation − Rev. 375, and (bottom) for a ‘bad’ observation − Rev. 447. The spectral enhancement is clearly due to the ‘patch’ region.

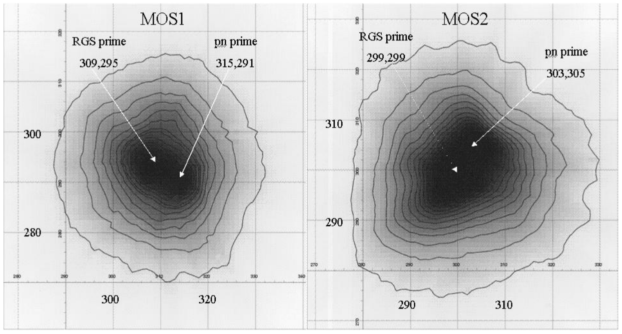

Figure 5. Co-added all-pattern, all-energy central CCD images from all imaging mode MOS observations (up to Rev.∼900) (central regions shown). Grey-scale and contours show numbers of photons incident. The RGS- and pn-prime boresights (for MOS1 and MOS2) are also marked.

2.1. The ‘Patch’ − Where is it?

So, what is this patch, and why is it only seen in a few observations? The answer to this second question became clearer when we looked at the observations in more detail. Almost all of the MOS observations were set, usually due to requirements of the pn camera, such that the remnant was not placed directly at the centre of the MOS detectors, but was usually offset (by ∼2-3 arcminutes). In fact the *only* observations where the remnant was placed at the centres of the MOS detectors were the observations in Rev. 433 & 447 − i.e. the *only* observations where the MOS ‘patches’ and the corresponding spectral shifts were observed.

This suggested that the ‘patches’ have something to do with the large numbers of photons incident at the very centres of the MOS detectors. Most *XMM-Newton* observations are performed in such a way that the target source lies at the optimum position in one or more of the main instruments. The spacecraft has been constructed such that these optimum positions, the individual instrument boresights, lie approximately coaligned. As most observations have been set up with either pn or RGS as the ‘prime’ instrument, these two boresights, the pn boresight and the RGS boresight (which lie very close to one another, separated by only ≈10 arcseconds) are the aimpoints of the vast majority of all the *XMM-Newton* observations. Consequently, these areas will have been impacted by very many photons. To test this, and obtain the degree of photon incidence, we co-added all-pattern, all-energy central CCD images from every single imaging mode MOS observation (up to Rev.∼900). The central regions of the central MOS CCDs are shown in Fig.5, and show that the peak in photon incidence does indeed lie at the centres of the MOS detectors, in a roughly oval region surrounding the positions of the RGS- and pn-prime boresights.

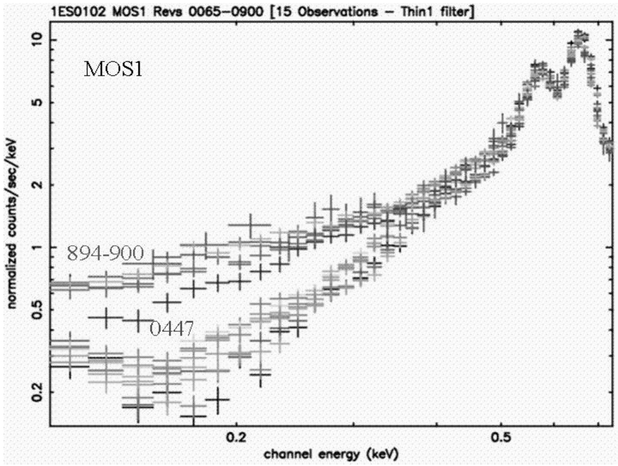

Figure 6. The 10 MOS1 spectra of 1ES0102-72 from Fig.2 plus those from Revs. 894/900. These more recent spectra show an even more marked behaviour in terms of a shift in spectrum, compared with the only previous on-boresight observation (Rev. 447).

2.2. The ‘Patch’ − How big is it?

In an effort to test our hypotheses so far, and to ascertain the size of the ‘patches’, an on-boresight raster observation of 1ES0102-72 was performed in Revs. 894/900 (of the 4 observations, one was very effected by flare activity). In looking first at the spectral properties, it was seen that all the Revs. 894/900 spectra showed similar spectral-shift behaviour to that seen in the earlier on-boresight (Revs. 433/447) observations, but to an even greater degree (the MOS1 spectra are shown in Fig.6). The situation is similar in the case of MOS2, but with subtle differences: In performing the ‘on-patch’-‘off-patch’ spectral analysis, as for Fig.4, we see that, in the case of MOS1, the on-patch effect may have already reached a peak by Rev 447, with little evolution thereafter, whereas off-patch, a moderate evolution in spectral shift is still seen at later times. In the case of MOS2, the situation appears the same, although a lag is observed with respect to MOS1 − the MOS2 on-patch effect has not yet reached a peak by Rev 447, and there is moderate evolution thereafter (perhaps reaching a peak), and off-patch, only a little effect is seen by Rev 447, and moderate evolution is seen thereafter.

Keeping in mind the idea that the patch is an area on the detector, not on the remnant, it was possible to create an image of the patch, using (for each MOS) the following method: All ‘good’ off-boresight sky (i.e. RA/Dec) images were mosaiced together to obtain a 0.1−0.35 keV image of the non-patch remnant. Using our knowledge of the remnant position on the detector and the observation position angle, this mosaiced image was rotated and flipped to the correct detector position and orientation for each ‘bad’ on-boresight pointing. Correcting for the relative exposures, this rotated/flipped image was subtracted from each ‘bad’ on-boresight detector-coordinate image, to obtain images of the remainder − the patch. A final

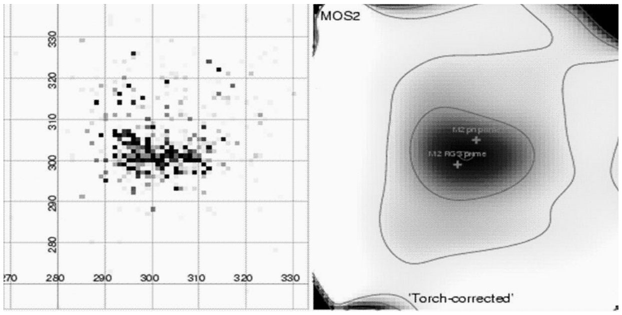

Figure 7. Final 'torchlight-corrected' images of the MOS2 patch (see text): left, raw; right, smoothed. (The crosses mark the pn- and RGS-prime boresights.)

correction is necessary to account for the unusual effect of the patch only being visible when the SNR illuminates the particular area of the detector – in effect, 1ES0102-72 acts rather like a torchlight. Once this correction is made, raw and smoothed final mosaics of the MOS1 and MOS2 patches can be constructed (the MOS2 patch is shown in Fig.7).

3. COUNTERING THE EFFECTS OF THE 'PATCH'

3.1. Software

The low energy redistribution function (RMF) of the MOS CCDs has a complex shape, in that the main photopeak has a secondary component (a shoulder) which relatively increases with decreasing energy, until, at the very lowest energies, it is the dominant component (see Fig.8). A new on-boresight rmf was constructed to account for the temporal changes seen in 1ES0102-72, RX J0720.4-3125, Zeta Puppis and other sources. The form of this was such that the original (Fig.8) shoulder had now evolved into a flatter 'shelf', of lower amplitude, but extending to lower energies.

This has also now been incorporated into the *XMM-Newton* Science Analysis Software (the SAS), such that, as of SAS v6.5, there are now *three* RMF regions on each of the two MOS detectors – a 'patch core' region, a 'patch wings' region and an 'outside patch' region (see Fig.9). This, in combination with the 10 temporal epochs now considered in the SAS, gives rise to a total of 60 MOS RMFs in the current calibration files. For a source extracted close to the patch (e.g., as in Fig.9), a PSF- or flat-weighted average RMF can be constructed (automatically in the SAS) from the three region-defined RMFs (making use, of course, of the calibration files from the correct epoch).

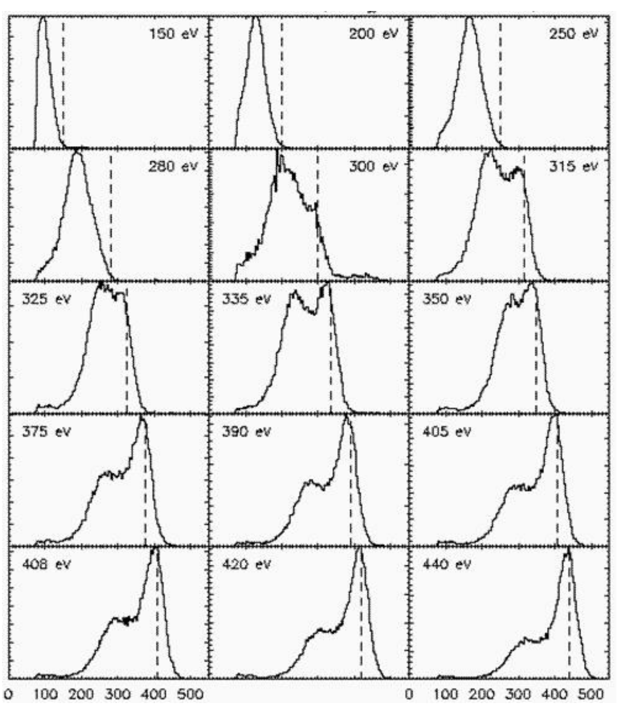

Figure 8. The low energy redistribution function (RMF) of the MOS CCDs (ground calibration measurements: Orsay synchrotron). The secondary component (shoulder) relatively increases with decreasing energy, until it is the dominant component.

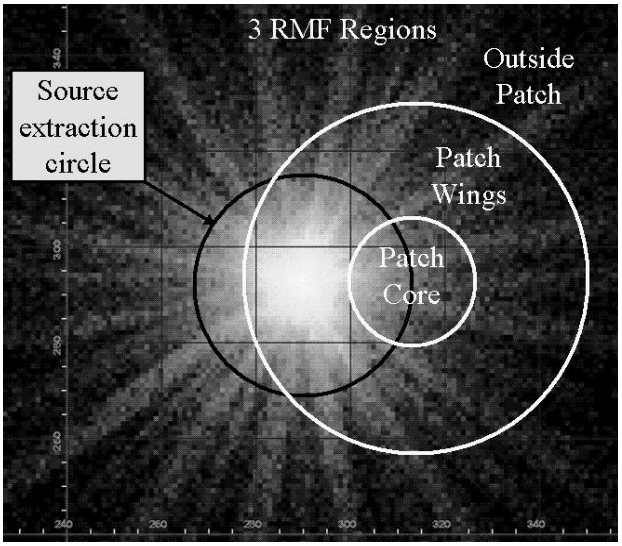

Figure 9. The XMM-Newton Science Analysis Software (SAS) situation, as of SAS v6.5: Three RMF regions are considered on each of the MOS detectors (see text).

Has this then improved the situation? Various tests have been performed on a large number of sources, and a great improvement has been seen overall. Fig.10 shows an on-boresight patch-effected spectrum from the core

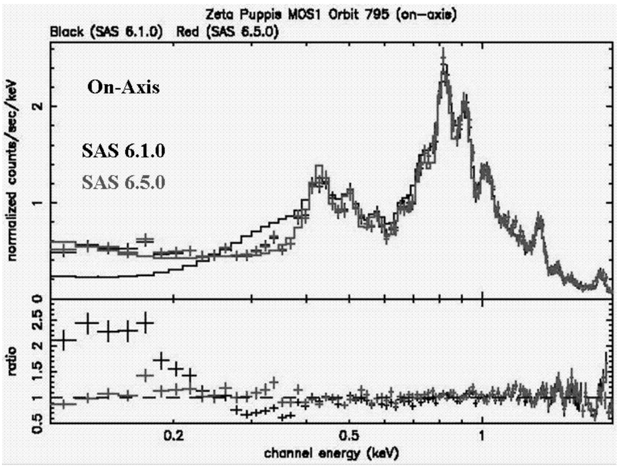

Figure 10. Improvement in RMFs: Usage of a SAS 6.5 RMF (grey) shows a great improvement over usage of a SAS 6.1 RMF (black) in fitting an RGS fluxed model to an on-boresight patch-effected spectrum of the core of Zeta Puppis from Rev. 795.

(0−15 arcseconds) of Zeta Puppis from Rev. 795. RMFs have been constructed using SAS 6.1 and SAS 6.5, and a high-resolution RGS fluxed model has been used to fit the data. As can be seen, usage of the SAS 6.1 RMF gives rise to a very poor fit, particularly at low energies. Usage of the SAS 6.5 RMF however, gives rise to a very much improved fit. Note also that tests performed on the wings (15−40 arcseconds) of Zeta Puppis show an improvement as well with SAS 6.5, but it is not so marked, as the effect of the patch is not so strong in the wings, at least at the present time, as discussed earlier.

3.2. Hardware

As regards the patches, and what is happening physically within the CCDs, the situation is not entirely clear. A single MOS pixel has an etched area (created to improve the low-energy quantum efficiency), situated near the centre of the surface area of the pixel. Typically, single pixel events (mono-pixels) are detected away from pixel edges, and therefore the majority of these are detected from these etched (open phase) areas. Conversely, double pixel events (bi-pixels) are detected from the pixel edges, i.e. away from the etched areas, and tend to be underneath the electrode structure. It has long be known, e.g. from calibration data taken pre-launch, that there is a difference in the redistribution shapes of mono- and bi-pixels, in that the charge loss shoulder in mono-pixels is much stronger than that in bi-pixels. The probable cause of this is thought to be that the charge collection in the open (etched) phase is less efficient, due to the structure of the potential field near the surface. Whatever the cause is, we are now observing that this potential structure is changing with time. This, together with the fact that we have a spatial coincidence of the area where this change is occurring most markedly and rapidly with the area of the detector where most photons are incident (the boresight, see Fig.5), indicates that we need to investigate the effects of large numbers of incident X-rays on the spectral redistribution properties of the MOS CCDs.

To this end, we are planning to reproduce the ‘patch effect’ in the X-ray test facility at Leicester University, using undamaged and proton-damaged CCDs of the same batch as those flying on *XMM-Newton*. MCP optics have recently been added at the optical centre of the Leicester facility to focus a beam of bremsstrahlung X-rays from the low-energy source of around 1.5 keV. We will then be able to monitor the response of these CCDs at low energies.

4. CONCLUDING REMARKS

This paper can be summarized as follows:

- A change in the redistribution properties of the *XMM-Newton* EPIC-MOS central CCDs has been discovered.
- The effect is such, that photons up to ~ 0.5 keV are redistributed to lower energies.
- The effect is seen to be evolving with time.
- The effect is seen to be spatially localized, and is greatest at the boresights of the instruments, where most of the incident X-rays over the mission lifetime have impacted.
- Detailed observations of the SNR 1ES0102-72 have now yielded the position and size of the effected ‘patch’.
- Temporal- and spatial-dependent response matrix generation has now been correctly implemented in SAS 6.5 to account for the effects of the ‘patch’.
- We are planning to reproduce and test the ‘patch effect’ in the X-ray test facility at Leicester.

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REFERENCES

Turner M.J.L., Abbey A., Arnaud M., et al. 2001, A&A, 365, L27