MICROMETEOROID DAMAGE TO CCDS IN XMM-NEWTON AND SWIFT AND ITS SIGNIFICANCE FOR FUTURE X-RAY MISSIONS

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ABSTRACT

Key words: X-rays; detectors; micrometeoroids; grazing incidence mirrors.

In 5 years of operation there have been 3 cases of presumed micrometeoroid damage at the focal plane CCDs on XMM-Newton. The latest hit resulted in one peripheral CCD in one of the MOS cameras stopping working and the central CCD developing a hot column which showed an unexpected slow decay over several weeks. The Swift XRT camera has already had a hit after 7 months in low earth orbit resulting in an over-range hot column and inability to operate in all modes. This paper discusses the information we have on these hits, ground tests at dust accelerators, probability of damage in the different orbits, and extrapolation to missions such as XEUS in L2 orbit.

1. OVERVIEW OF THE PROBLEM

This paper while largely an overview of micrometeoroid damage to the detectors on *XMM-Newton* and *Swift* tries to give some figures for the debris population in orbit and explains how this debris can get to the detectors. We also give thoughts on other existing missions with grazing incidence optics, details of further research at Leicester and speculation on future X-ray missions such as *Astrosat* and *XEUS*.

XMM-Newton launched by ESA in November 1999 is in a two day highly elliptical orbit with an apogee of c. 114,000 km and a perigee of c. 7000 km. The *EPIC (European Photon Imaging Cameras)* X-ray cameras use CCDs behind thin light blocking filters to record the images and spectra of celestial X-ray sources focused by the three sets of grazing incidence X-ray mirrors of 7.5m focal length. There is one camera at the focus of each mirror, and two of the cameras (hereafter, MOS1 & MOS2) each contain seven *MOS (Metal Oxide Semiconductor)* CCDs manufactured by E2V, while the third camera contains German *pn CCDs* (Turner et al. 2001). The *XRT* camera on *Swift* contains just one of the MOS CCD22s as used on *XMM-Newton* behind a set of 12 nested grazing incidence X-ray mirrors.

XMM-Newton has had a number of events during its 5+ years in orbit. Both pn and MOS cameras have experienced damage in the form of hot pixels sometimes proceeded by light flashes and there is strong evidence that these are due to micrometeoroids. The latest event in March 2005 resulted in the loss of a whole CCD in MOS1. *Swift* in low earth orbit has already sustained one hit after 6 months of operation. The *pn* team visited a dust accelerator in 2002 and showed that particles of micron size can be deflected by grazing incident optics onto the CCD (Meidinger et al 2002).

2. MICROMETEOROID HITS MECHANISM

In the same way that grazing incidence mirrors reflect X-rays, they can also deflect grazing incidence particles. As long as the high-Z surface is sufficiently smooth compared with the particle size and the particles angle of incidence is low enough the mirrors appear to be able to either deflect the particles or to break them up and create a shower. This was established by the MPE dust accelerator tests in 2002. The flux directly entering the telescope will be constrained within a narrow cone defined by the opening angle of the telescope. Both *Swift* and *XMM* telescopes with multiple-shell grazing incidence mirrors have similarly small grazing incidence angles, $\leq 0.7^o$. The MPE work shows that, at small angles, particles scatter essentially parallel to the mirror surface implying inelastic scattering of the particles when they strike the mirror surface. Transverse momentum is lost to the mirror but longitudinal momentum is conserved in the particle or its fragments. This result holds true out to grazing angles of 4^o, and possibly beyond (because the MPE measurements stopped at 4^o). Fig. 1 shows an SEM photograph of an impact site of an iron particle of

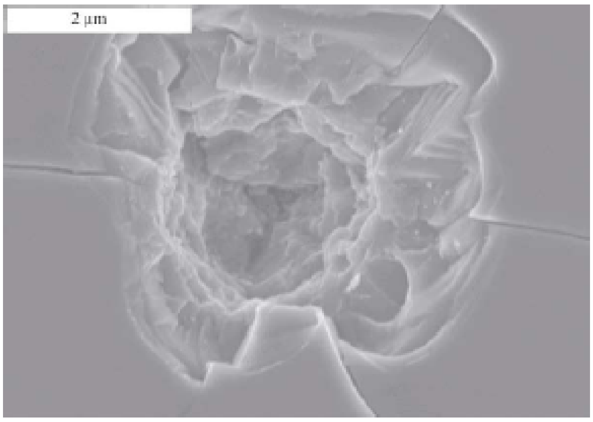

Figure 1. SEM photograph from pn study of an impact site in silicon of a 0.2 - 2µm iron particle

size 0.2 - 2μm with a speed of 5km/s in silicon from the MPE study. The light blocking filters are too thin to offer any protection to the CCDs except when the EPIC filter wheel is in the "closed" position.

For a spacecraft like *Swift*, in LEO, particle fluxes impacting on spacecraft surfaces may originate from interplanetary micrometeoroid particles intercepting the spacecraft orbit or from space debris particles created from anthropogenic activities in nearby orbits. The micrometeoroid component takes the form of an isotropic distribution which has been characterised by Grun et al and is sometimes known as the Interplanetary Meteoroid Flux or IMF. In LEO, there is a significant orbit-dependent space debris component, which sits on top of the micrometeoroid distribution. Knowledge of these two components provides a means of evaluating the probability of space particle impacts on *Swift*.

Figure 2 is a plot from a recent study by J. Carpenter 2005 using the ESA Master 2001 model of the meteoroid and debris environment between LEO and GEO as applied to the orbit of the Swift satellite and shows the flux rate for each face of the spacecraft versus particle size. At no time does the XRT have either ram or Earth pointing vectors. Calculations have therefore been restricted to flat plates with left, right, space and wake pointing directions. The XRT pointing direction varies as at it slews about the sky. In this simple model the XRT is assumed to spend equal time in each of the 4 described pointing directions. Once total impacts for each face shown in figure have been calculated, the average $impacts/m^2/sr/year$ is calculated. This is then multiplied by the XRT open area of 250cm^2. and an assumed acceptance cone angle of 10^o ($\pm 5^o$) for particles. The calculated number of impacts in the XRT focal plane in one year, by particles with diameters greater than 1μm is 1.4. The predicted rates for XMM with its mirrors of 1750cm^2 might be a factor of up to 10X higher as shown in Fig. 3.

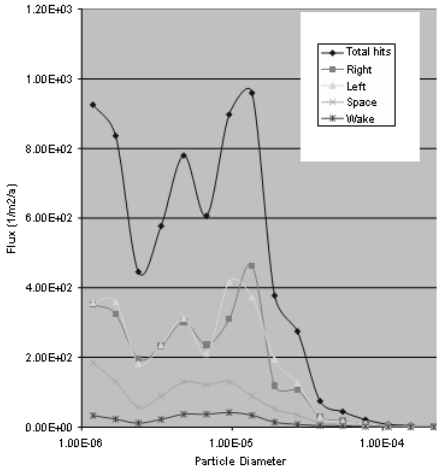

Figure 2. Impact flux contributions from each face for Swift

Impact Parameter (µm)	Impact Event Rate /year XRT 5°Cone half angle	Impact Event Rate /year XMM 5°Cone half angle
1	2.4	20
2	0.7	6.0
5	0.2	1.9
10	0.1	1.0

Figure 3. comparison of Swift and XMM impact rates excluding low earth orbit RAM direction

3. XMM IMPACT HISTORY

Each orbit of *XMM-Newton* takes 2 days. The following lists the impacts seen so far:

- Orbit 107 17 July 2000 MOS2 patch of hot pixels on 3 CCDs - questionable whether was due to large proton flare prior to Filter Wheel closing.
- Orbit 156 15 Oct 2000 PN several hot pixels suddenly appear.
- Orbit 325 17 Sept 2001 MOS1 bright flash seen, many new hot pixels.
- Orbit 490 - 12 Aug 2002 - MOS2 - bright flash seen, no new hot pixels
- Orbit 961 9 March 2005 MOS1 bright flash seen, bright column developed on central CCD, total loss of CCD6.

3.1. The effect of the suspected impact on orbit 107

The new hot pixels shown in Figure 4 formed a patch on CCDs 1,2 and 7 on MOS2 at the start of orbit 108 but were not present at the end of 107 when a high radiation level was reported. The filter wheel would have been closed for the perigee pass, so should have protected the CCDs. This mystery was never officially solved. There must have been a hit in the time between the end of the observation and the closing of the filter wheel. The distribution of hot pixels suggested that a cloud of debris from an impact higher in the camera had hit the focal plane.

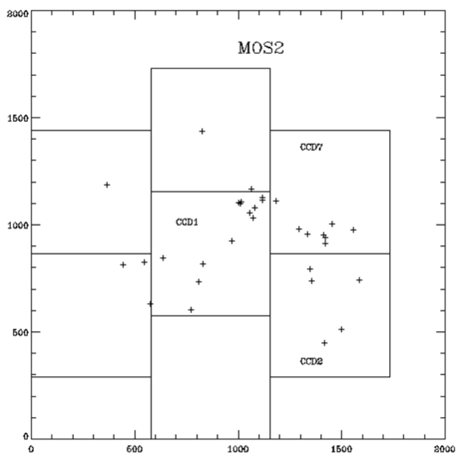

Figure 4. Hot pixels at start of orbit 108

3.2. Impact on pn camera orbit 156

This is an extract from the 2002 SPIE paper on the PN-CCD impact and dust accelerator verification from Norbert Meidinger et al: "XMM was observing Zeta Puppis and was 115000 km from Earth and pointing 60 from the ram direction. The hot pixels generated had energies orders of magnitude higher than those expected due to heavy ions." Figure 5 shows the 35 hot pixels which appeared after this impact covering 6 of the 12 CCDs. The 12 CCDs cover an area of 6cm X 6cm. The circles indicate where several hot pixels are close together with the number shown alongside.

3.3. Impact on MOS1 on orbit 325

This was the first event where a light flash was seen. The first evidence was that in a routine observation the MOS1 camera suffered a "FIFO FULL" error where its data buffers had received too much data. In figure 6 this 3-d image of a light flash was reconstructed from the partial images generated on-board due to FIFO overflow in the limited memory.

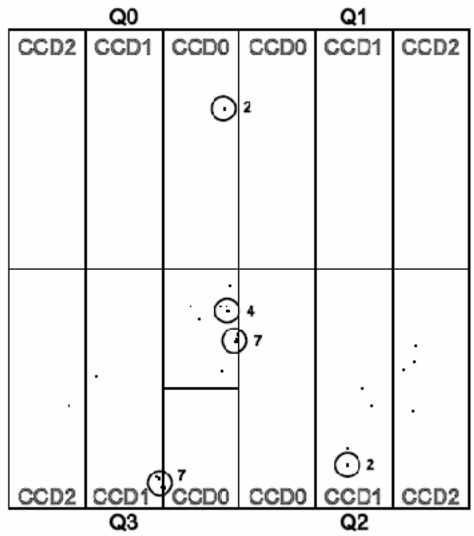

Figure 5. Hot pixels on pn camera during orbit 156

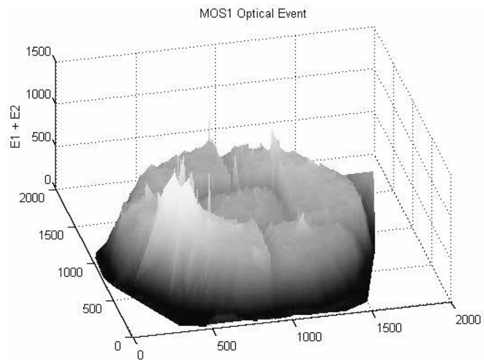

Figure 6. Orbit 325 - reconstructed optical flash in MOS1

3.4. Impact on MOS2 on orbit 490

This was first reported as a "FIFO Full" error in MOS2 during a routine observation which happened during the annual Perseid meteor shower and observations had been planned to go no nearer than 15^o to the Perseid radiant. The observation would have been 64^o from the radiant at this time, and the event was interesting as no hot pixels were generated and it is surmised that it happened high in the telescope because of the more obtuse angle than some of the other grazing incidence ones.

3.5. Impact on MOS1 on orbit 961

The impact on MOS1 during orbit 961 proved to be the most damaging to date in the life of *XMM-Newton*. At 01:30 hrs UT on 09 March, 2005 during a routine observation, the now familiar "FIFO Full" error occurred and the optical flash image in figure 7 was extracted from the

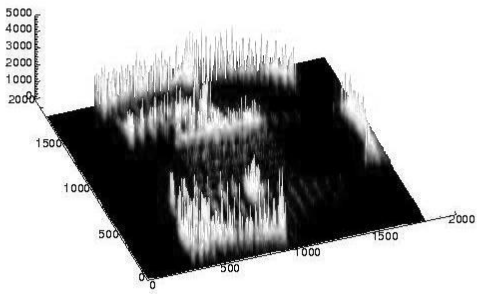

Figure 7. Orbit 961 - optical flash in MOS1

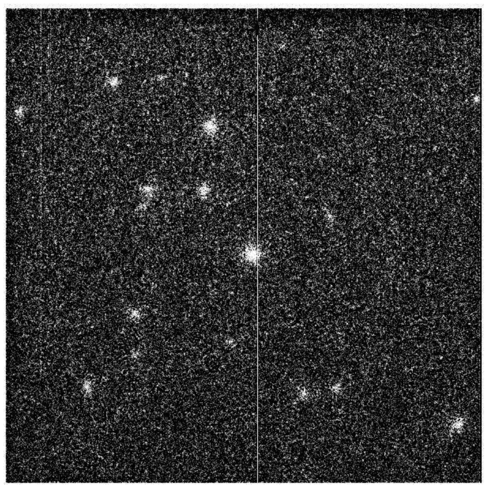

Figure 8. Orbit 961 - hot column in CCD1

buffers. After the flash CCD6 output was permanently saturated giving no x-ray events and a new hot column of value around 60DN had appeared on CCD1 - figure 8. Investigations took place to determine the failure mode of CCD6 and the conclusion was that there is a hard short from an electrode to the substrate which is injecting large amounts of charge irrespective of clocking. MOS1 now operates with CCD6 switched off. The hot column on CCD1 appeared to reduce a little over successive orbits (figure 9) and a subsequent adjustment to the bias level for the rogue column has restored normal operation. Since the MOS1 damage was extensive, a series of tests were performed during orbit 1042 on the thin optical filter which had been in front of the camera when the impact took place. The bright globular cluster Omega Centauri was observed, and the filter wheel moved by small increments to see if a pattern of out-of-focus light spots could be seen. The test was believed to be able to detect holes down to 50μm but none were seen. This work is still ongoing, but it does appear that the filter has not been significantly damaged by the impact. This is because each piece of debris is likely to be in the sub-micron/micron range and does not create an enlarged hole in a thin filter.

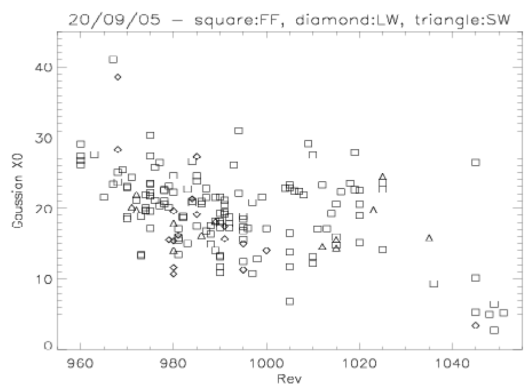

Figure 9. Hot column trend in CCD1 after orbit 961

4. SWIFT IMPACT

On 27 May 2005 *Swift XRT*, only 6 months into the mission the processing log shows the following:

Mode	Count rate	Time
PC	0.80	2005-147-05:21:48.708787
PC	1799.55	2005-147-05:21:51.216076
WT	1034.19	2005-147-05:22:4.7158214
LRPD	45758.71	2005-147-05:22:5.8755013
PUPD	45975.84	2005-147-05:22:7.2480145

This shows that the camera suddenly saw lots of events and went through its modes to the highest count rate mode PUPD. The XRT viewing direction at the time was 142^o from the RAM direction. Because of its large memory buffers *Swift XRT* was able to store all of the single frame of data which occurred at 05:21:51UT on 27 May 2005. Figure 10 shows the light flash stopping at the edge of the field of view. The dark areas in the centre of the bright areas are caused by the sum of the 3 X 3 event pattern exceeding a 4095 upper limit and therefore being interpreted on board as a cosmic ray and not being telemetered.

Figure 11 shows the resultant damage to the *Swift* CCD. The column down the middle of the image and the short columns were not present before the event. The damage does not obviously coincide with the peaks of the light splashes in the flash image.

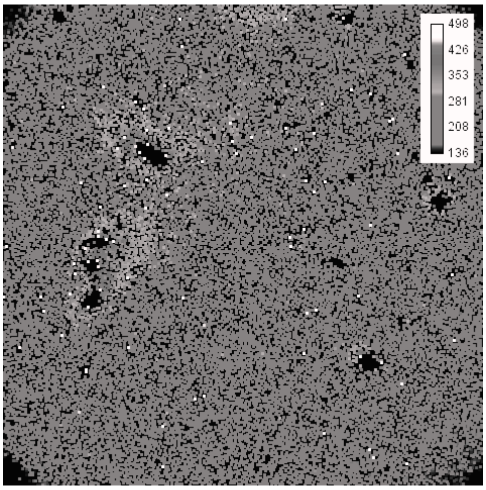

Figure 10. Light flash on CCD in Swift XRT

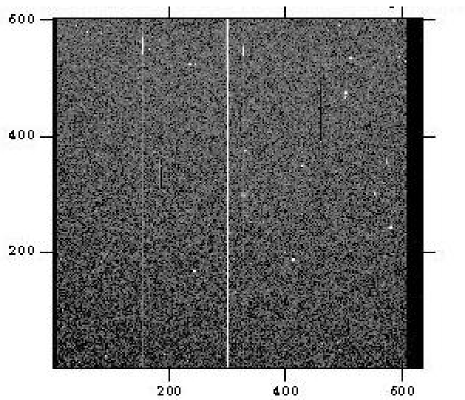

Figure 11. Bright columns resulting from the impact on Swift XRT

4.1. Operational effects of the XRT CCD damage

Although we have been able to exclude the hot column from the data on *Swift XRT* in photon counting and timing modes, we are currently unable make full use of the fast readout mode known as Photodiode mode. This reads out the whole CCD in diagonal strips by means of a column shift followed by a row shift and there is no positional information to remove defects. The hot column raises the background level to between half and full scale depending on the operating temperature. So far the science loss from this has been negligible, but on occasions, the earliest x-ray data from a GRB could be compromised. The spectrum of figure 12 shows a typical noise peak at over half of the ADC range from data taken at -59^{o}C on 23 Sept 2005 while pointing at Gamma Ray Burst GRB050922B. Changes to the gain used in photodiode mode are a possible fix to restore dynamic range at some loss of energy resolution. Another fix might be to read out the "good" half of the CCD avoiding the hot column with a need to offset point the spacecraft.

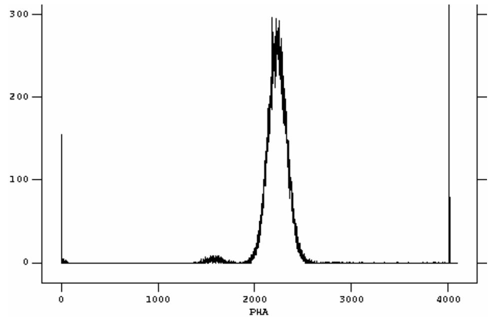

Figure 12. Resulting spectrum in PD mode of bright column on Swift XRT

4.2. Filter damage test

Swift has an advantage over *XMM* in that a light emitting diode can be switched on inside the camera to check filter integrity. Subtracting an early orbit test of the in-flight LED from a post-impact image showed no visible damage to the light-blocking filter which would have been a large bright out-of-focus area(s). So, as with the previous micrometeoroid events it seems that the size of hole which is generated in the filter is insufficient to cause a noticeable light leak yet sufficient to damage a hard silicon dioxide surface.

4.3. Swift pointing directions

Figure 13 shows the directions referenced to the Ram direction in which *Swift* pointed during the first 2 months of operation. Due to operational constraints *Swift* spends most of its time pointing around 90^{o} to the Ram direction so the major flux of low earth orbit debris should not have been a problem.

5. PAST AND FUTURE MISSIONS WITH GRAZING INCIDENCE OPTICS

This is a brief summary of past missions and what is known about the effect of micrometeoroids on the detectors:

- *Chandra* 6 years in orbit - in similar deep elliptical orbit to XMM-Newton, but no reports of impact damage. This is likely to be due to the geometry since the mirrors have 5X smaller effective area

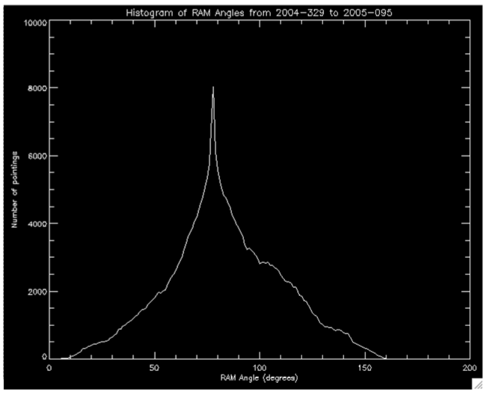

Figure 13. Swift pointing direction history

than *XMM-Newton*, so if we believe in statistics we should expect an impact anytime now!

- *ASCA* was in similar low earth orbit to *Swift*, but no reports of impact damage. Was this due to use of thin foil mirrors of 137m thickness? Perhaps incoming micrometeoroids are not deflected by such mirrors.
- *Rosat* was in a similar low earth orbit to *Swift* but its detectors were probably insensitive to damage from micron size particles. There are no reports of significant gas loss from the imaging proportional counters through window damage during its 9 year lifetime.

Future missions:

- *Astrosat* will be in a nearly equatorial low earth orbit and will use ASCA-like thin foil X-ray mirrors. Possibly the risk of particle damage may be correspondingly lower. AT UoL we will perform tests on mirror samples to ascertain whether the thin shells deflect micrometeoroids.
- *XEUS* will be in L2 orbit. It has a large mirror with an effective area of 10 x *XMM-Newton* which will produce a considerable potential for impacts. A narrower acceptance angle gives some reduction. Expect several hits per year unless L2 orbit debris is considerably different from XMM orbit. We would recommend that there is considerable effort spent on redundancy and avoiding knock-on effects of damage in one detector affecting others.

6. CURRENT RESEARCH INTO DUST DAMAGE AT LEICESTER

The University of Leicester along with MPE, Keyser-Threde and RKK Energia has been involved in an experiment on the ISS - 756 days in orbit with microchannel plates bearing a 60nm aluminium film. This was able to detect particles down to 14 nm diameter at 20km/s producing a 400nm hole in the foil. The density of holes showed a flux of over 1/m^2/s. It is likely that particles of this size may not damage the surface of a CCD, but one can speculate about the cumulative damage to thin filters. J D Carpenter et al 2005. A different experiment has recently been taking place at the Open University light gas gun facility to investigate larger particles and their effects on detectors but so far we have only shattered silicon wafers. It is our intention also to use the dust accelerator at the same location for tests on *Astrosat* thin mirror samples.

7. CONCLUSIONS

Micrometeoroid particles in low and high earth orbit present a considerable hazard to missions with grazing incident optics and impact sensitive detecor arrays. *XMM-Newton* has experienced approximately one hit per 14 months over its 6 years in orbit. *Swift* in low earth orbit may have been unlucky to have been hit in 6 months. Although the density of particles is highest in the Ram direction, no known hits occurred in that direction and it is usually avoided. Since the complete loss of a CCD from the last hit on *XMM-Newton*, we should consider carefully the redundancy aspects of focal planes for future missions. Would we have built *Swift XRT* with a single CCD had the *XMM* rev 961 event already occurred at the design stage? There is probably little else that can be done for missions with grazing incidence optics except to continue observing in the most favourable directions and to design mirror baffles so as to reduce the acceptance angle for particle fluences.

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