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# Evidence for micrometeoroid damage in the pn-CCD camera system aboard XMM-Newton

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**Abstract.** The mirror systems of the X-ray observatory XMM-Newton were designed to image X-rays up to 15 keV by grazing incidence reflection onto a focal plane, equipped with Charge Coupled Devices (CCDs). In orbit # 156 we have observed a sudden increase of about 35 "bright" pixels spread over 15 cm$^2$ in the pn-CCD camera system. The amount of locally generated leakage current cannot be explained by ionizing particles. We suggest that a micrometeoroid scattered under a small angle off the X-ray telescope mirror surface finally reached the focal plane detector and produced the damage.

**Key words.** XMM-Newton – back illuminated pn-CCDs – radiation hardness – micrometeoroids – interstellar dust

## 1. Introduction

The X-ray astronomy observatory XMM-Newton was successfully launched on Dec. 10, 1999 into a highly eccentric orbit with an initial inclination of 40°, a perigee of ∼7000 km and an apogee of ∼110 000 km. During each 48 hour orbit XMM-Newton passes the Earth's radiation belts, resulting in a non-operational period of the scientific instruments of approximately 8 hours. To avoid any damage by the radiation the scientific instruments are shielded by an equivalent of 3 cm aluminum. According to the current models of the radiation environment the detector is exposed to a total "equivalent" dose of $5 \times 10^8$ of 10 MeV protons per cm$^2$ in a 10 year mission time. This dose includes also the contributions from solar flares and ionizing nuclei of higher atomic number $Z$. One of the scientific instruments on board of XMM-Newton is an X-ray pn-CCD which was designed and built in such a way that it will not only survive the harsh radiation environment but that the energy resolution will not have degraded by more than 10% at the end of mission (Meidinger et al. 2000).

Shortly before the launch of XMM-Newton it became apparent that charged particles, in particular protons, could reach the unshielded open section of the CCD detectors via transmission through the X-ray telescope. The protons are reflected and scattered off the mirror surfaces like the X-ray photons if the energy and the incidence angles are adequate (Aschenbach 2001). The CCD ACIS experiment on NASA's X-ray observatory Chandra, which also has an orbit passing the Earth's radiation belts, was heavily affected by such protons with energies of up to several hundreds of keV in the first four revolutions. A major degredation of the spectroscopic performance was observed (Prigozhin et al. 2000).

On XMM-Newton we have recently observed a different kind of damage, which cannot be explained by ionizing radiation of single ions. In orbit # 156 a sudden increase of the count rate indicated a local formation of bright pixels. For a definition of bright pixel see Sect. 3. About 35 pixels were involved, randomly distributed over one half of the focal plane. The effect increased for a while until it stabilized after 2 days. The 35 pixels were hit simultaneously, i.e. within less than 50 milliseconds. We suspect that dust particles (micrometeoroids) have produced the bright pixels. The affected area is less than $2 \times 10^{-4}$ of the sensitive area, so that the loss of scientific data is negligible, but the effect is relevant in terms of instrument safety and long term reliability. In addition it is scientifically interesting to understand the physical processes which lead to transmission of the suspect dust particles through the grazing incidence X-ray mirrors and to the detector damage.

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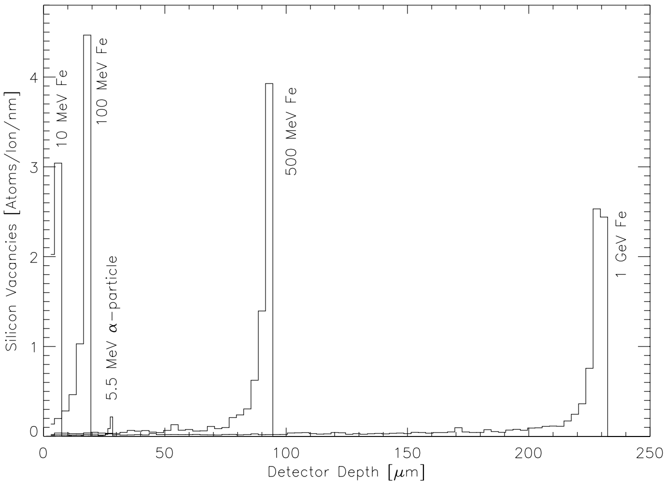

**Fig. 1.** The "Bragg" curves for $\alpha$–particles and iron atoms in silicon were simulated with SRIM, developed by Ziegler et al. (1999). The lattice damage is shown as a function of penetration depth in the silicon. The damage by iron atoms was calculated for 10 MeV, 100 MeV, 500 MeV and 1 GeV. If the damage by 6 MeV $\alpha$–particles is normalized to one, the integrated damage along the track of 100 MeV iron atoms is about 45 larger, the one by 1 GeV iron atoms, 230 $\mu$m deep in silicon is roughly 75 times higher than the damage by $\alpha$–particles.

First we describe the basic operational principles of the back illuminated, fully depleted pn-CCD. The main emphasis of the paper is the presentation of the experimental evidence for a micrometeoroid damage. Estimates of the probability of such an origin of the damage are supported by simulations.

## 2. The concept of fully depleted pn-CCDs

The basic principles of the pn-CCD camera built under the leadership of the Max-Planck-Institut für extraterrestrische Physik, as part of the European Photon Imaging Camera (EPIC) for XMM-Newton were described recently by Strüder et al. (2001). The whole detector volume (6 cm × 6 cm × 300 $\mu$m of silicon) is sensitive to radiation. The pixel size was chosen to $150 \times 150\ \mu\text{m}^2$, adapted to the design angular resolution of the XMM-Newton X-ray telescopes. One full frame exposure (400 pixels × 384 pixels) is read out in 73 ms. The extended full frame mode uses a total frame time of 199 ms, the large window mode 48 ms and the timing mode 0.03 ms.

The electronic read noise is about 5 electrons (rms) yielding a Fano limited energy resolution for energies >1 keV. The pn-CCD is illuminated through the homogeneous back surface of the chip which consists of an ultra-shallow rectifying $p^+$ implant in a phosphorus doped bulk. The quantum efficiency for X-rays is >90% from 500 eV to 10 keV. 6 MeV protons are stopped just within the detector volume. Alpha particles of the same energy have a penetration depth of about 30 $\mu$m, iron atoms of 10 MeV are stopped in a depth of 3 $\mu$m (see Fig. 1).

In front of the detector a filter wheel is mounted (Turner et al. 2001; Strüder et al. 2001). The thicknesses of the filters vary between 2000 Å and 4500 Å of polypropylene and aluminum. Before orbit # 156 in October 13, 2000, the bright pixel performance was as expected from ground calibrations: 20 pixels in the whole camera were set "bad" to reduce the telemetry rate.

Since commissioning, calibration and performance verification the detector has been working very well.

## 3. Damage of semiconductor detectors

During orbit # 156, in XMM-Newton's eclipse season, a sudden increase of the count rate was indicating a non-conformal behavior. The event happened during the observation of Zeta Puppis (RA = 08h 03m 35s, Dec = −40d 00m 12s) at UT 2000-10-15T07:41:50. The distance to Earth was 115 000 km. The pn-CCD camera was operated in the "Large Window Mode" with the medium filter in front of the detector's entrance window. The angle between flight direction and observing direction was 60° in the heliocentric coordinate system. Approximately 35 new "bright" pixel were instantaneously showing up. "Bright" means, that the electron content of the charge cloud in the pixel is above the event threshold at least in every tenth frame, independent of the operating mode (except for timing and burst mode). The most seriously hit device is CCD0 of quadrant 3. Figure 2 shows the bright pixel pattern produced by the event. A close-up of that region and a time series of images is depicted in Fig. 4. The light curves of some of the bright pixels of CCD0, quadrant 3 are given in Fig. 3. Within the time resolution of the instrument (∼50 ms), all pixels show the increased count rate simultaneously.

### *3.1. Phenomenology of the damage*

As can be seen in Fig. 4 some of the pixel clusters on the right-hand side of CCD0 show an increase of detector leakage current with time: Just after the hit the leakage current was well localized in the damaged pixels (image 2, upper row, middle). In the third image, 11 hours later, some pixels on the right-hand side showed some blooming effect, i.e. spilling of charges in the neighboring pixels in transfer direction[1]. In image 4 (lower left), 46 hours later, the heavily damaged pixels have increased the generation of leakage current, indicating that those columns were heavily affected. From then on, the leakage behaviour has stabilized. By shifting the event threshold from 100 eV to 150 eV or 200 eV respectively, the columns became clean again. We can easily calculate the leakage current generation in the final state. The two most heavily damaged areas in this CCD are generating more than

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[1] Please note, that the integration times between both exposures differ by a factor of 4.

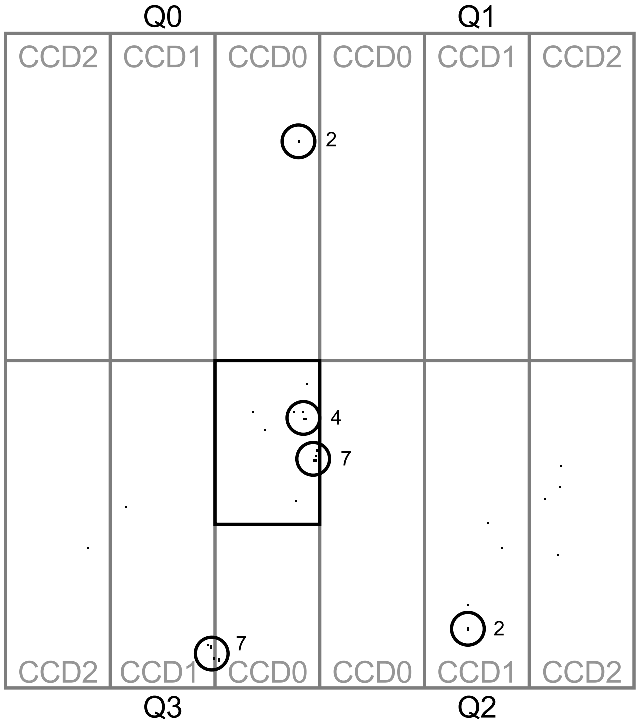

**Fig. 2.** Pattern of bright pixel distribution, occurring in orbit # 156. With the exception of one hit in quadrant 0, CCD0 all sources of bright pixels are located in an area with a radius of approximately 2 cm. The most severely hit device is CCD0 of quadrant 3. A time series of the framed area (CCD0, Q3) is shown in Fig. 4. The focal point of the X-ray telescope is located in the lower third of CCD0 in quadrant Q1.

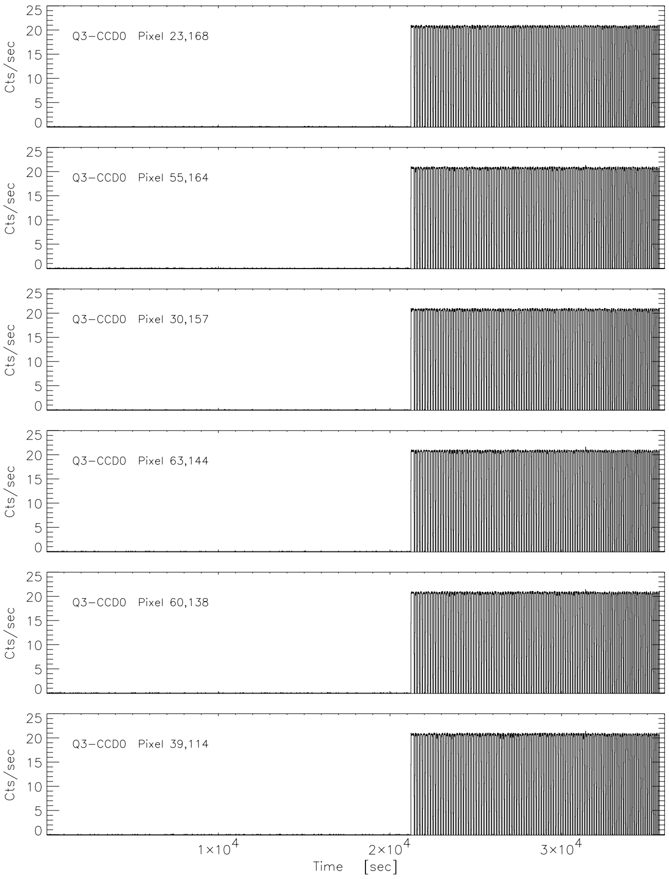

**Fig. 3.** Count rate increase in orbit # 156. Within one time resolution element, the 6 selected pixel of CCD0, quadrant 3, went into saturation, i.e. 21 event hits per second, which is 1/0.0477 counts per second in the large window mode.

$10^{-14}$ A per hit at an operating temperature of –90 °C. This is roughly $10^8$ times more than we would expect from a 6 MeV alpha particle and about $10^6$ more than an iron atom of 1 GeV (see Bragg curves simulated with SRIM in Fig. 1). A similar analysis was made for other pixels. There is no way to explain the instantaneous dramatic increase of leakage current by ionizing radiation: electrons, protons or heavy ions. In principle a single isolated defect may be explained by the effects of a highly ionising particle hitting an area of already heavily predamaged silicon. However, it seems very unlikely that such heavy damage occurs simultaneously at 35 positions of the detector.

It occurred that in orbit # 108 on July 11, 2000, a similar event happened in the MOS2 camera (Turner et al. 2001) on XMM-Newton: More than 30 pixels showed a significant increase in local leakage current and thus noise. They became "bright", similar to the previously given definition. They were finally commanded "bad".

### *3.2. Micrometeoroid damage of silicon detectors*

Since the simultaneous occurences of 35 bright pixels cannot be explained by any event involving protons or heavier ions we suggest that it may be caused by a micrometeoroid impact. The walls of the optical bench will absorb small particles, but it is conceivable that micrometeoroids reach the detector through the X-ray mirror system. This is not possible on straight paths but by scattering at the mirror surface. In principle, at least three scenarios can be envisaged to produce the observed effects:

(a) a micrometeoroid entering the mirror system under grazing incidence conditions may stick in the gold layer and lead to a forward ejection of gold particles;
(b) a fluffy micrometeoroid dust particle may disintegrate at grazing reflection;
(c) a micrometeoroid passing through the mirror system by scattering effects may hit the filter located in front of the CCD detector and produce secondary ejecta.

While the impact of dust particles onto surfaces has been well studied under normal incidence conditions in the laboratory, e.g. by ESA (1998) there are no data for grazing incidence hits. However, it is plausible that under grazing incidence a large fraction of the incoming particle's energy will reach the focal plane. Assuming that the X-ray telescope effective aperture, i.e. open area times acceptance solid angle, is about the same for dust particles and X-rays (21.5 $\mathrm{cm}^2$ ster) one can estimate the rate of particles hitting the CCD detector using the micrometeorite mass spectrum measured by

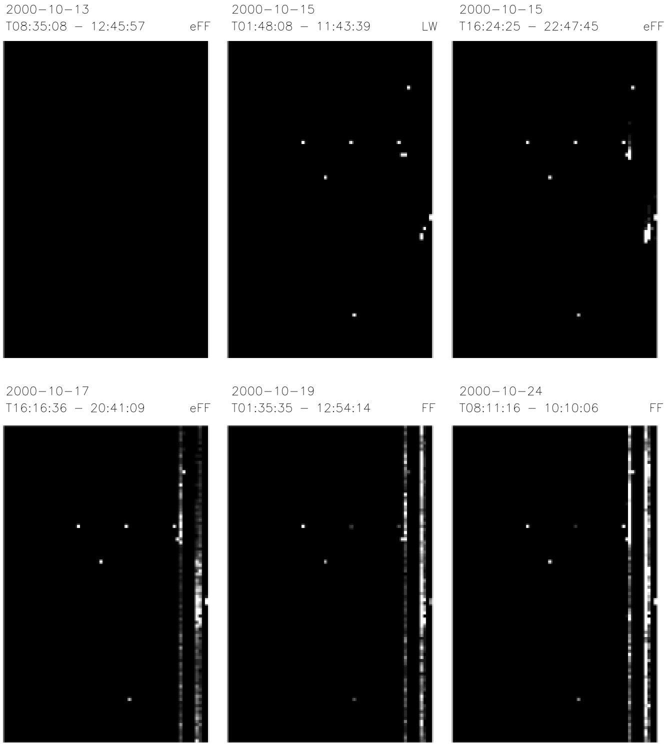

**Fig. 4.** Hit pattern of the suddenly appearing bright pixels in orbit # 156. The six images of CCD0 in quadrant 3 span a time of 11 days in total. The first (clean) image was made in the extended Full Frame mode (indicated as eFF), the second in the large window mode (LW), image 3 and 4 again in eFF and pictures 5 and 6 in Full Frame mode. The behavior seems to become stable after 4 days, to be seen at image 4 on October 17.

Gruen et al. (1985). The typical particle mass matching the observed rate of events of $\sim 2$ yr$^{-1}$ and telescope is $m \sim 10^{-11}$ g, corresponding to a particle size of 0.5 $\mu$m. We note that a dust particle of this mass travelling at interplanetary speeds ($\sim 30$ km s$^{-1}$) has a kinetic energy of $\sim 3 \times 10^{13}$ eV, viz. plenty to cause the observed effects in the pn-CCD detector. Since the penetration depth of such a dust particle is just a few microns in silicon it delivers all its energy in a relatively small volume giving rise to a huge ionization density. On the contrary, a single ion as heavy as iron of the same energy simply traverses the silicon and the ionization density in the silicon, responsible for the damage, is orders of magnitudes smaller. In fact, the highest ionization damage is produced by those iron ions which are completely stopped in the silicon and they have an energy of some GeV and they fall short in ionization density by $10^5$ (see Bragg curves in Fig. 1) to explain the observed damage in the silicon at our operating temperature.

## 4. Conclusions

In the EPIC pn-CCD camera on XMM-Newton we have observed a sudden increase of "bright pixels". The degree of local damage is too high to be explained by ionizing radiation. We have provided evidence that these events are caused by micrometeoroids impacts entering the telescope through the X-ray mirror system. The two occurrences of the sudden bad pixel increase do certainly not proof the funneling of micrometeoroids through XMM-Newton's X-ray telescopes. But the type and time structure of the damage as well as the estimated frequency of such events suggest the damage of the CCD being produced by a micrometeoroid reaching the detector via the X-ray telescope. The physics of such a process, however, have still to be studied. Such experiments related to the interaction between swift dust particles and mirror surfaces under grazing incidence conditions are planned by us for the near future in the "dust accelerator" at the MPI für Kernphysik to test the "reflectivity" of dust particles of various sizes and velocities and grazing angles.

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