Low-Energy Proton Effects on Detectors on X-Ray Astronomy Missions

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Abstract

It has been found that protons of energies in the range of hundreds of keV to a few MeV can scatter at low angles through the mirror shells of space-based X-ray astronomy missions. These protons, because of their low energy can produce a high non-ionising dose in unshielded CCDs and are therefore a potential threat. This paper discusses the efforts made in the context of the ESA X-ray Multi-Mirror (XMM) mission to simulate the processes involved in the transport of protons and generation of non-ionising dose in CCD's. The tools used for this analysis included the Geant4 Monte-Carlo toolkit, used for fully three-dimensional calculations. Another code, TRIM, was used to examine details of the low angle scattering in one dimension.

Keywords: X-ray, astronomy, spacecraft, proton, CCD

1 Introduction

X-ray astronomy in space relies on the focussing of X-ray photons by low-angle scattering from shaped 'shells'. In most cases the 'optics' consist of two sets of nested concentric shells with shapes near to sections of cones. Two grazing-incidence scatters result in focussing of the X-rays on the shell axis. ESA's X-ray Multi-Mirror (XMM) mission [1] has three mirror modules of outer diameter 70 cm, each consisting of 58 nested shells which focus the X-rays onto CCD detectors some 7 m from the mirrors.

The U.S. X-ray observatory Chandra recently experienced unexpected degradation of the majority of the CCDs in its ACIS instrument. Since Chandra is in a similar orbit to the XMM, there has been concern over the effects on these instruments. This paper summarises analysis to date by the ESA Space Environments and Effects Analysis Section of the problem.

It has become clear since the symptoms were first observed on Chandra that the problems were due to low-energy ($\sim$100 keV) protons reaching the focal plane after scattering through the mirror shells. The observed damage characteristics are highly suggestive of large-scale displacement damage. Furthermore, the damage was observed in 'front-illuminated' devices where the sensitive channel is some microns from the surface while 'back-illuminated' devices where particles have to penetrate only some tens of microns further were undamaged.

The main tool used for this analysis was the Geant4 Monte Carlo toolkit [2], developed by a world-wide collaboration of high-energy physics laboratories and institutes. The physical process at the focus of the study, low-angle scattering of low-energy protons, is not one that has received much theoretical or experimental study. Therefore comparisons with a well-established one-dimensional program, TRIM, and with experimental results from Columbia University, were also carried out as part of the effort to analyse the problem.

2 Geant4 models

Geometrical models of both the Chandra mirrors and one of the three XMM mirrors, together with the associated detectors, were implemented in Geant4. These models were used to simulate the response of the instrument to the radiation environment encountered on orbit. In particular, the interactions of low-energy protons with the telescope module and the effects these will have on the performance and survivability of the detectors were addressed. The mass model of one of the XMM telescope mirrors, X-ray baffle and grating systems, consisting of more than 1000 individual elements, is shown in Figure 1. At the focal plane simple collecting areas represented the two detectors EPIC and RGS. The telescope mirrors were modelled as 58 shells, each made of four contiguous conic sections: two representing the parabolic shaped mirror and further two the hyperbolic shaped mirror.

2.1 Particle Generator

In the Geant4 simulations presented here, the initial particles were protons of various energies. For the incident particle positions and directions, the user could choose from a list of predetermined options. All of the simulations performed in the current study were using the so-called 'aperture' option, where an isotropic distribution of particles was generated within a cone, the half-angle of which corresponds to the field of view of the mirror. The position of the source was randomly sampled over an incident area which was specified as a disk positioned immediately in front of the X-ray baffle.

2.2 Physics Processes

The physics processes included in the Geant4 simulations were:

- Hadron ionisation, with knock-off electron (δ-ray) production; hadron multiple scattering, including the lateral displacement of the particle; electron ionisation; electron bremsstrahlung; electron-positron annihilation; muon ionisation; muon bremsstrahlung; muon pair production; photoelectric effect; Compton scattering and γ-conversion.

Of these, the first two are the most important ones for analysis of proton propagation in the XMM and Chandra mirror systems. For a detailed discussion on the physics and the implementation of the various processes, see the Geant4 physics reference manual [2].

3 XMM simulations

A suite of XMM simulation runs was performed for protons of various energies in the range 100 keV to 3 MeV. For each proton energy, a series of runs were conducted where the angular distribution of the protons was sampled isotropically over different conical half-angles, ranging from 0.5 to 30 degrees. For each XMM run four different transmission efficiencies were calculated:

1. The efficiency of protons to scatter (at least once) off the mirror surfaces,
2. The efficiency of protons to travel through the X-ray baffle and mirror surfaces without a single interaction,
3. The efficiency of protons in reaching the RGS detector,
4. The efficiency of protons in reaching the EPIC detector.

It was found that the efficiency of the XMM mirrors in scattering protons varies more strongly with the angle of incidence than with energy. Apart from the more readily absorbed 100 keV protons, the efficiencies of the more energetic protons were very similar.

The efficiency of the protons in reaching the EPIC and RGS detectors was determined both as a function of source half-angle and as incident energy. The results largely reflect the behaviour caused by the interaction with the mirrors themselves, i.e. the efficiency is a stronger function of source half-angle than proton energy, increasing sharply up to $\sim$4 degrees, beyond which any increase is very shallow.

4 Chandra simulations

A Geant4 model was also implemented for the Chandra spacecraft [3], including the High Resolution Mirror Assembly (HRMA), optical bench, magnetic broom, internal baffles and ACIS camera detectors. The only difference between the XMM and Chandra simulations was the geometry of the spacecraft. Both simulations shared the code responsible for generating a distribution of particles incident on the spacecraft, as well as the physics modules.

The efficiency with which protons propagate through the mirrors was estimated from the number of protons recorded at the dummy detector volume placed behind the mirror. As for XMM, the efficiency of the mirror is a strong function of the incident direction of the protons rather than their energy. Tests were conducted for source half-angles up to 10 degrees, where the efficiency starts to flatten out.

A comparison between the results obtained for the XMM EPIC and Chandra ACIS cameras shows that they have very similar efficiencies to protons propagating down the mirrors. At 1 degree source half-angles, 600 keV protons have almost identical efficiencies at the EPIC and ACIS. At 10 degrees the efficiency of the EPIC is 70% of that of the ACIS camera, although this gain is probably balanced out by the fact that the XMM orbit is a somewhat harsher environment.

5 Comparisons with TRIM and experimental data

One-dimensional geometry simulations from TRIM [4] formed the basis of choosing the Geant4 parameters to ensure it was providing realistic low-angle scattering results. Runs for various angles of incidence from 1 to 90 degrees were performed using the two codes for proton energy ranges from 100 keV to 1 MeV.

Initially, the number of low elevation angle scattering protons was significantly lower in the Geant4 results as compared to those by TRIM, but the exit energy distributions were in reasonable agreement. Fitting the elevation angle distribution by tuning the Geant4 step-cut parameters resulted in the exit energy distribution deviating further from the TRIM distribution. Given the critical dependence on the low angle distribution of the scattering particles, it was considered more important to tune Geant4 to fit its elevation angle distribution to the TRIM results at the expense of the energy distribution.

Proton reflectivity measurements of XMM grating and mirror samples were also performed at the Harvard University Accelerator for Materials Science by the Columbia group [5]. This data provided the means to experimentally verify the Geant4 simulations. It was found that there was a good agreement between the Geant4 1-D grating results and the Columbia experiment. Both sets of data peak at similar scatter angles and follow the same form, although the Geant4 ”reflection” efficiency was slightly higher than the experimental value; see Figure 2. For the purposes of the simulation and the present analysis work, this agreement was regarded as very good.

6 Conclusions

Monte-Carlo simulations have been performed to verify that protons of energies in the range of hundreds of keV to a few MeV can scatter at low angles through the mirror shells of X-ray astronomy missions such as Chandra and XMM. These protons, because of their low energy and at times large populations can produce a high non-ionising dose in unshielded CCDs, and are therefore a potential threat. Efforts were discussed made in the context of the XMM mission to simulate the processes involved in the transport of protons and generation of non-ionising dose in CCD's. The main tool used for this analysis was the Geant4 Monte-Carlo code, which was found to be a flexible and suitable tool for the type of highly demanding radiation analysis work such as reported here.

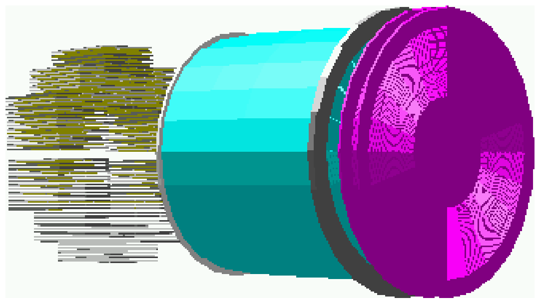

Figure 1: XMM geometric model used in Geant4 simulations. From the right, this shows three baffles, the set of nested mirror shells and the reflection gratings. It was not necessary to model the spacecraft telescope tube which closes the optical axes between the gratings and the detectors 7 m away. Particles enter from open space to the right, and detectors (not shown) are to the left.

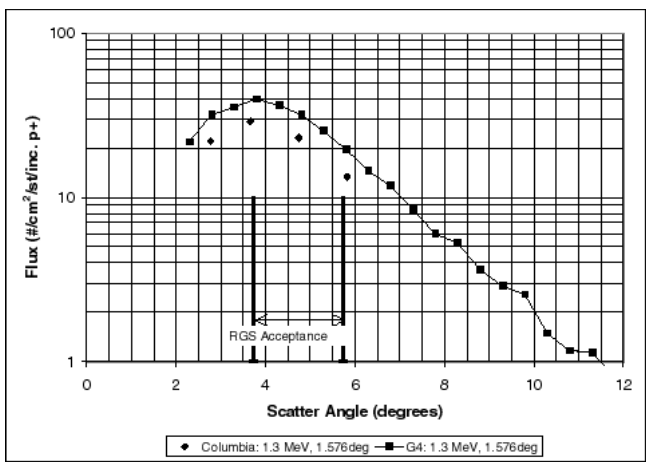

Figure 2: Experimental low-energy proton data vs. Geant4 simulation.

References

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