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Background information and technological tests of hard X-ray detectors

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Abstract. Hard X-ray detectors for astronomical observations are currently being designed with advanced background rejection capabilities, based on high level of pixelisation and on fast signal processing. The development of such devices, based on room temperature semiconductor such as CdTe or CdZnTe comes through extensive testing programs normally based on ground campaigns, using radioactive sources, X-ray tubes and particle beam accelerators. These methods show their limits, however, especially for the measurements of the response to the different types of hadrons. Firtsly, we briefly review the knowledge of the primary sources of background and of the different radiation environments both for space and balloon altitudes, for which typical fluxes/rates are given. Then, we discuss how flying prototypes on high altitude balloons can greatly help to test the detector performance in an environment almost as severe as the conditions found in orbit, with detectors responding at very similar rates.

Key words. X-ray: Background – X-ray: Detectors – X-ray: Observations – Long Duration Balloons

1. Introduction

Prediction capability and understanding of X-ray detector backgrounds for space applications have significantly advanced in recent years, thanks to the availability of data from radiation monitoring experiments and the use of publicly available modelling tools. This is of great help for the design of the instruments, including the prediction of their sensitivity performance. However, innovative aspects of instrument design need to be tested from direct experience especially when they include complex electronics architecture. We explicitly refer here to the relatively recent application of room temperature semiconductor arrays based on CdTe or CdZnTe (hereafter, CZT) crystals. These devices are best suited to build high spatial resolution arrays with relatively easy manufacturing and assemblying into large area structures. This was largely demonstrated by the construction of the two coded mask telescopes, INTEGRAL/IBIS (Ubertini et al. 2003) and SWIFT/BAT (Barthelmy 2000) and by their successful operation in space with ca-

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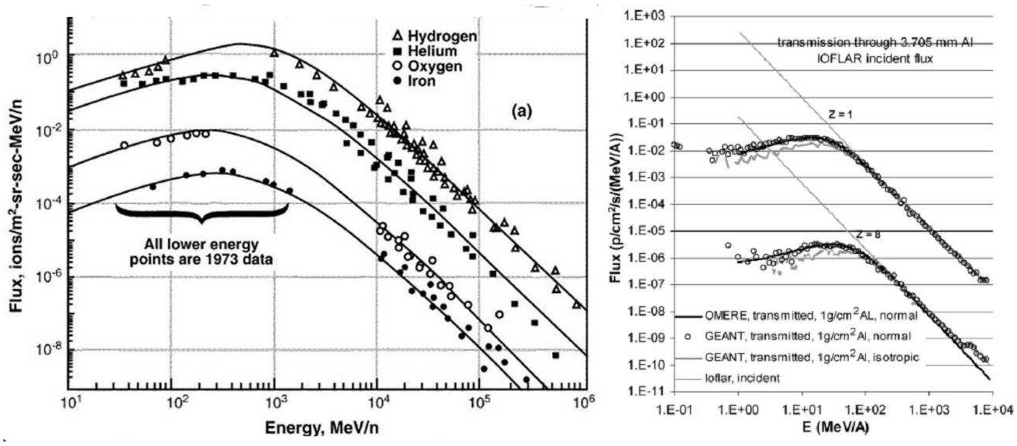

Fig. 1. Left: the spectrum of Galactic Cosmic Rays (Parnell et al. 1998). Right: spectra obtained from solar flare model, given a 707km, 98 deg inclination orbit. Both incident spectra, and spectra transmitted through a 3.7mm Al shielding are shown for protons and oxigen ions (Inguimbert & Duzellier 2004). Solar protons are softer than GCR and the Al absorber provides efficient shielding at the lower energies.

pability of surviving several years of severe radiation environment. New type of pixel detectors have been developed in recent years (and are now available also commercially) based on the coupling of relatively large (up to ~2-3 cm) crystals to multi-electrode arrays. In this way from a single crystal a position sensitive CZT sensor can be obtained. One known problem of semiconductor detectors is that, due to the poor mobility of holes in the crystal compared to that of electrons, the signal amplitude for a given energy will depend on the depth of the energy deposition site. The charge loss in the crystal must be taken into account to reconstruct correctly the energy deposition. This can be done for each photon event, by recording and analysing the signal shape. One given detector configuration should then have a well defined pattern of signal formation in the multipixel sensor, as a response to single energy deposition. This also means that a background event, eventually leading to a continuos distribution of energy losses in the detector volume, can be recognized and eliminated from the good event stream. The main astrophysical motivation for this effort is the requirement for next generation hard X-ray astronomy missions, to undergo a real step forward in sensitivity by reducing instrumental background by at least a factor of $\sim$ 10 compared to the currently flying experiments.

2. Background sources

The noise background measured in hard X-ray detectors in orbit or at balloon floating altitudes is influenced by the environment created by the geomagnetic field, being a function of several parameters including geomagnetic latitude and height for balloons and the orbital parameters for satellites.

Sources of internal detector background are: galactic cosmic rays (see Fig. 1, left panel); solar energetic particles (SEP), namely particles accelerated in solar flares and by shock waves in coronal mass ejections; particles, primarily cosmic rays trapped in the Earth's radiation belts. Satellites in low Earth orbits (LEO) may encounter temporary background enhancement from particles trapped within the South Atlantic Anomaly (SAA) region, which is formed by an extension of the inner Van Allen belt. The SAA boundaries depend on altitude and then varies for each orbit (as an example, see the image by the ROSAT X-ray satellite, shown at NASA/ROSAT site

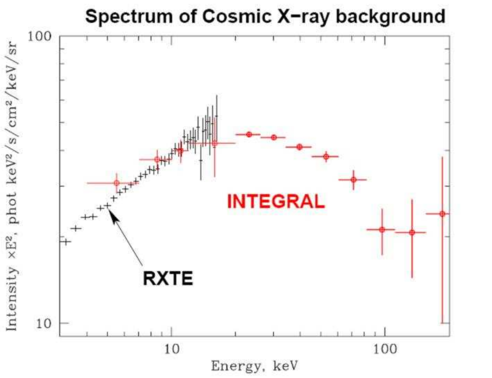

Fig. 2. Left: recent measurements of the spectrum of the Cosmic X-ray background by RXTE and INTEGRAL (Churazov et al. 2007).

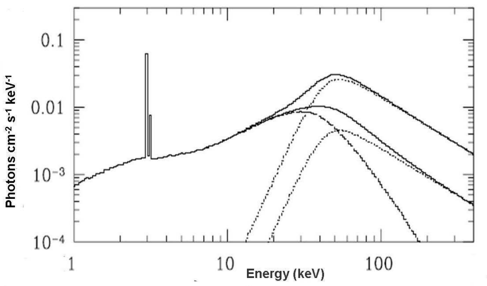

Fig. 3. X-ray spectrum of the atmospheric emission from the Earth (total X-ray surface brightness), corresponding to observations of a geomagnetic polar region at solar minimum and from geomagnetic equator at solar maximum (Sazonov et al. 2007).

page [1]). An additional, important contribution to the total detector rate is given by the Cosmic X-ray Background (CXB) formed by a diffuse, isotropic emission of X-rays of extragalactic origin. For moderately large or wide field-of-view instruments, like coded mask telescopes such component is usually dominant at energies below ~ 50 − 100 keV. The spectral energy distribution of the CXB radiation is shown in Fig 2.

GCR are mostly formed by protons (about 84%) with the remainder being composed by about 13% of alpha particles, 2% of electrons and 1% of heavier nuclei. They are less intense for balloon or LEO flight trajectories as the Earth magnetic field acts as a shield, preventing a particle with rigidity [2] less than a given "cutoff" value to reach a given point in the magnetosphere. However, GCR and SEP can induce significant background via collision of the particles on athmosphere target nuclei. A single collision may release numerous secondary particles via nuclear interaction cascade, the most important components being neutrons and X-/γ-rays. This "Earth albedo" radiation is an important background source for balloon and LEO flights. It is highly dependent on cutoff rigidity and therefore, highly modulated (Gehrels 1985, 1992). In Fig. 3 is shown the spectral distribution of the total X-ray surface brightness of the Earth, as modelled by Sazonov et al. (2007) based on the known primary cosmic ray spectra and on transport code simulations. The model is found to be in agreement with observations of albedo X-rays (see a list of references in the Sazonov et al. (2007) paper). In addition to this almost stable component, variability of the atmospheric albedo can be produced by relatively strong SEP events, see e.g. Share & Murphy (2001).

The zenith-dependent and omnidirectional energy spectrum of albedo neutrons has been measured by balloon flight experiment at a geomagnetic latitude of 40 degrees (Palestine) by Preszler et al. (1972). The authors found that the atmospheric flux of secondary neutrons is not isotropic and peaks towards the zenith (see fig. 4). The effect is evident especially at the lowest neutron energies. Balloons floating at altitudes corresponding to a few g/cm^2 will experience incident neutron flux coming preferentially from the bottom.

In summary, orbits with trajectories mostly outside the magnetosphere are mainly concerned with primary GCR and SEP component, while LEO and balloons have mostly to deal with induced atmospheric background and with a less intense GCR primary component, both dependent on local geomagnetic environment.

[1] http://heasarc.gsfc.nasa.gov/docs/rosat/gallery/display/saa.html, credit: Snowden

[2] given a particle of charge q and momentum p, the rigidity is given by $R = pc/q$.

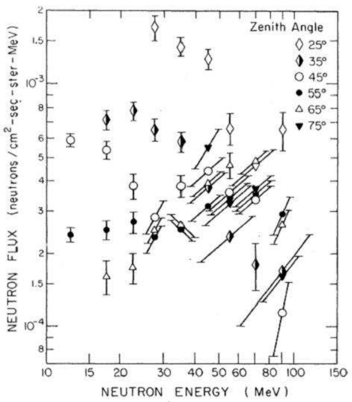

Fig. 4. Directional, zenith-dependent energy distribution of albedo neutrons measured during balloon flight from Palestine (Preszler et al. 1972).

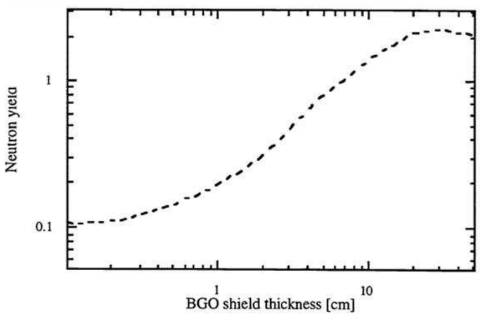

Fig. 5. Estimation of neutron flux inside a BGO shield as a function of its thickness (Naya et al. 1996). Neutrons are produced by decay of unstable nuclei induced by the bombardment of the instrument by cosmic rays. The y-scale is normalized to a configuration with 7.5cm thickness.

3. Prediction tools

The knowledge of GCR spectra and fluxes of the primary components, along with the structure of the Earth magnetosphere are the basis of standard mathematical/empirical models, like the NASA AP-8 (protons, Sawyer & Vette 1976) and AE-8 (electrons, Vette 1991) mapping fluxes and spectra of particles trapped in the radiation belts. In addition, *de-facto* reference models can be considered JPL 91 (Feynman et al. 1991) for solar protons, CREME86 (Adams Jr. 1986) and CREME96 (Tylka et al. 1997) for GCR. At the lower energies ($E < 20$ MeV for protons) particles can be easily stopped by a passive shield equivalent to a few mm of Al (see Fig. 1, right panel), while higher energy particles need to be shielded by the use of active anticoincidence (AC) devices.

The interaction of a single high energy cosmic ray particle with the active parts of the detector may give rise to signals following a nuclear interaction cascade. These signals may be either prompt or delayed, the latter component being induced by the decay of isotopes following material activation. The implementation of thick shields, which are useful for the stopping of the secondary γ-ray component will also cause significant activation. An example related to BGO is described in Fig. 5.

In order to find the best tradeoff for optimization of the shielding configuration and also the design of the readout electronics for active detector parts, photon and particle transport codes can be used to simulate the response of the system to the radiation components. The outcome is the evaluation of the energy depositions in the different materials using input spectra and fluxes computed by the above described models. Most popular transport codes are GEANT-4 (Agostinelli et al. 2003) and EGS-4 (Nelson et al. 1985).

4. Background in CZT detectors

We investigate the interesting possibility given by balloon flights for testing background suppression techniques in CZT detectors. CZT prototypes have already been flying at balloon altitudes in different shielding configurations. A completely shielded small detector (zero aperture, active lateral and bottom shielding) flown on balloon from Alice Springs has measured volumetric rates of about $\sim 10^{-3}$ and $\sim 2.5 \times 10^{-4}$ counts cm^{-3} s^{-1} keV^{-1} at 100 keV and 200 keV, respectively (Parsons et al. 2004). These intensities appear to be a factor ~ 8 lower than the internal background level experienced by the INTEGRAL/IBIS CdTe detector, flying in high Earth orbit (HEO). This can be explained as due to different factors: the more severe environment experienced by IBIS in HEO; the more effective shielding setup of the small balloon detector and finally, the difference in the mass of the surrounding material (massive spacecraft and payload components on INTEGRAL).

As a matter of fact, the requirements for future CZT space experiments for use in astronomy are based on high spatial resolution (~mm or even less) and higher spectral performances and background rejection capabilities than those currently flying on satellites. For these new generation detectors, predicting background rates could be a more difficult task than for current devices due to the presence of more complex geometry and/or more elaborated signal processing. An example is the CZT instrument shown in Fig. 6, designed as detection plane for a focusing soft γ-ray telescope working in the energy range 10-1200 keV (Natalucci et al. 2008). The instrument combines 4 CZT detection planes with side coverage by additional CZT detector and active BGO shield. The top CZT plane is a 5mm thick, 0.8mm spatial resolution detector and is designed to be used to record the focal spot formed by imaging cosmic sources by multilayer mirror up to an energy of about 250 keV.

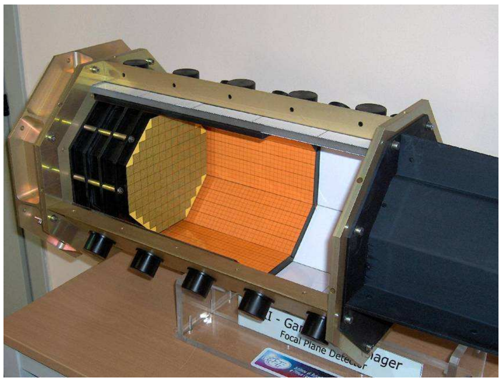

Fig. 6. A soft $\gamma - ray$ detector based on 4 CZT position sensitive detection arrays, to be used in the focal plane of a Laue lens telescope. The spatial resolution of the top detector (yellow modules) is 0.8mm.

5. Prospects

Clearly, flying prototypes on high altitude balloons is the most direct way to test the performance of these detectors and to provide a platform of validation for numerical modelling.

In order to develop and study the response of a new generation CZT pixel detector with depth sensing capability we plan to use the small CZT prototype SIDERALE (Quadrini & Caroli 2008) on a series of balloon flights, the first planned from Arctica (Svalbard station). The instrument implements a series of 5mm thick CZT sensors and an advanced readout electronics with recording of different signal parameters for each event. A flight from Svalbard will be useful to test the prototype under difficult background conditions, as those expected in this Arctica region with high fluxes of particles, including protons, secondary neutrons and γ-rays. In addition, it will provide a valuable set of data to be analyzed in order to improve the electric design of the CZT detector against key performances such as correct energy reconstruction and background events rejection.

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