Chapter 5

The HEX background simulation

This chapter discusses various sources of background in space-based radiation detectors and the simulation of the background of the HEX detector in a lunar environment, using Geant4.

Since the Earth’s atmosphere absorbs x-rays and γ-rays, detectors have to be sent above and out of the atmosphere, either on balloons or on satellites, to observe celestial sources of x-/γ radiation. Outer space is not a complete vacuum, but contains dust, energetic particles (nuclei of atoms, electrons and neutrinos), and electromagnetic radiation. This intense ambient radiation environment interacts with the material of the detector and the spacecraft, producing secondary particles. These can interact with the detector, its surrounding material and shields to produce a background or noise against which feeble celestial signals have to be measured. This background is called instrumental background and is sensitive to the material used for the detector, the distribution of mass around it, including the shielding components used. Instrumental background is very mission specific; it depends on the mission profile, i.e., the orbit type, inclination, altitude, and the solar activity during the mission.

There also exists the pervasive cosmic diffuse x-/γ-ray background which is largely homogeneous and isotropic in nature. When these photons enter the detector aperture, they add to the detector background. X-/γ-ray detectors that are used for remote sensing the surfaces of planets with little or no atmosphere (Mars, Mercury and the Moon), have to deal with planetary “albedos” that enter the detector, either directly through its aperture, or indirectly after interacting with its housing and shields. These “albedos” are produced by the interaction of high energy radiation with planetary surfaces or atmospheres.
Thus, the total background observed by a space-based radiation detector can be expressed as

\[ b_{\text{total}} = b_{\text{instr}} + b_{\text{diffuse}} + b_{GCR} + b_{\text{albedo}} \]

where \( b_{\text{total}} \) is the total observed background, \( b_{\text{instr}} \) is the instrumental background, \( b_{\text{diffuse}} \) is the background in the detector due to the diffuse photon component, \( b_{GCR} \) is the induced background due to GCRs, and \( b_{\text{albedo}} \) is the background due to albedo radiation.

The sensitivity of a hard x-ray/soft \( \gamma \)-ray detector (tens of keV to hundreds of MeV) is limited by detector background and the low photon intensity at these energies. Sensitivity of a detector is defined as the minimum source flux that it can measure, taking into account various factors, like the total background recorded by the detector, the exposure time etc. Thus, precise determination of the detector background is essential in making accurate predictions of the sensitivity of the detector to various energies, for pre-determined exposure times and required statistical significance of the results.

### 5.1 Components of the Space Radiation Environment

The space radiation environment within the solar system consists of galactic cosmic rays (GCRs), and electromagnetic and particulate radiation from the Sun. Due to the influence of the solar magnetic field, the intensity of cosmic rays with energies less than 1 GeV vary with solar activity. This is called solar modulation. The isotropic cosmic diffuse x-rays and \( \gamma \)-rays also pervade interplanetary space. The HEX instrument on Chandrayaan-I is designed to measure the intensity of spectral lines in the 30-270 keV region from the surface of the Moon, at an orbital altitude of 100 km. So, from the point of view of this experiment, the radiation that enters the detector through its aperture are the lunar \( \gamma \)-ray and neutron albedos produced by the interaction of the high energy GCR protons with the lunar surface.

#### 5.1.1 Galactic Cosmic Rays

Galactic cosmic rays are high energy particles that are composed of 87% protons, 12% helium nuclei, and electrons and heavier nuclei, and originate from outside the solar system. They are basically atomic nuclei which have been stripped off their electrons by energetic processes. Primary cosmic rays are those that are accelerated by astrophysical sources. Secondary cosmic rays are produced by the interaction of these primaries
with the interstellar medium during their propagation through the galaxy, for example, lithium, beryllium and boron, which are not abundant end-products of stellar nucleosynthesis.

GCRs with energy up to $10^{21}$ eV are produced by shock acceleration in supernova remnants (SNRs), active galactic nuclei (AGN). GCRs originating from SNRs are not accelerated by the explosion itself. The remnants of the explosion are expanding clouds of gas and associated magnetic fields that can last for thousands of years. The second order Fermi acceleration of the energetic charged particles within the expanding magnetic clouds results in energy gain. These particles ultimately gain so much energy that they cannot be contained by the remnant and so escape into the galaxy. The amount of energy gained by the cosmic rays depend on the size of the acceleration region and the complexity of the magnetic field.

GCRs are affected by magnetic fields. The interplanetary magnetic field, embedded with the solar wind varies with the solar activity, increasing during solar maximum. This magnetic field deflects and excludes GCRs with energies below 1 GeV/nuc, thereby decreasing the intensity of low energy particles. This is how solar modulation takes place, and it results in the anti-correlation of the GCR intensity at low energies with the solar activity. Figure(5.1) shows the GCR proton spectra for various values of solar modulation, corresponding to solar minimum, solar maximum and average solar activity. These spectra have been calculated from [8b] using the formula expressed in eqn(2.9).

![Figure 5.1: Galactic cosmic ray proton spectrum calculated from [8b] for different values of solar modulation parameter. For the HEX background simulation, the solar modulation parameter chosen was 550 MeV, which corresponds to average solar activity.](image-url)
5.1.2 Solar Energetic Particles

Solar Energetic Particles (SEPs) are high energy particles coming from the Sun, consisting of protons, electrons and heavy ions. SEPs can originate from either of these two processes:

1. **Solar Flare**, a violent explosion that takes place in the chromosphere and corona of the Sun, heating the plasma to tens of millions of Kelvins, and accelerating electrons, protons, and heavy ions to high energies and produce electromagnetic radiation across the spectrum. Flares occur at sunspots, where intense magnetic fields emerge from the Sun’s surface into the corona, and releases the stored magnetic energy through what is generally believed to be a reconnection process. Streams of highly energetic particles are released into the solar wind, which can enter the Earth’s magnetosphere.

2. **Coronal Mass Ejections (CMEs)** are bursts of highly energetic plasma caused by the release of magnetic energy at the Sun. They are not always associated with solar flares. The thin plasma in the heliosphere is shocked when a CME occurs, causing the generation of electromagnetic radiation and acceleration of charged particles. When these particles hit the geomagnetic field, temporary deformation of its structure can occur, causing reconnection of the field at the side of the Earth that is not sunlit. This results in the entry of charged particles into the Earth’s atmosphere where they cause auroras.

For the SEPs to reach the Earth or Moon, the particles need to first propagate through the corona to the foot of an interplanetary magnetic field line by diffusion. This can cause significant attenuation of the particle intensity if the distance between the acceleration site and the field line is large. The particles have to travel through interplanetary space along the magnetic field lines which adopt a spiral configuration during solar quiet periods. Diffusion and acceleration by interplanetary shocks can cause scattering of the particles in the medium, resulting in quasi-isotropic fluxes.

5.1.3 Lunar Gamma-ray and Neutron Albedos

Lunar albedo particles are produced due to the interaction of high energy protons from GCRs and SEPs with the lunar crust. The γ-ray spectrum measured by the Gamma-ray Spectrometer (GRS) on the Lunar Prospector (LP) gives abundance information of elements on the Moon like Oxygen, Silicon, Titanium, Aluminum, Iron, Magnesium,
Calcium, Potassium and Thorium. Potassium and Thorium decay by natural radioactivity, while the other elements emit $\gamma$-rays during de-excitation due to neutron activation. Inelastic scattering and capture of neutrons produced by incident high energy protons generate $\gamma$-rays. Reference [1e] states that $\gamma$-rays produced by neutron-induced reactions occur at depths of $\sim 140$ g cm$^{-2}$ of material, and the scattering of $\gamma$-rays within this mass thickness causes a continuum of $\gamma$-ray energies to escape the crust along with nuclear lines. These weak lines superimpose the dominant continuum, resulting in their decreased detection sensitivity. In this present study, this simulated continuum spectrum or the lunar gamma-ray albedo (LGRA) was used to determine the background measured by the HEX CZT detector. The continuum is shown in fig(5.2).

![Plot of the differential Lunar Scattered Gamma-ray flux from 1keV to 10MeV](fan600spec.txt u 1:3)

**Figure 5.2:** The lunar gamma-ray albedo (LGRA) from [1e] for the lunar material, ferroan anorthosite. This spectrum ranges from 1 keV to 10 MeV and is simulated using Geant4 by bombarding a lunar target material with GCRs. The intense line at 0.511 MeV is due to electron-positron annihilation.

The lunar neutron albedo (LNA) was measured by the Neutron Spectrometer (NS) of LP. The results of measurements of thermal, epithermal and fast neutron flux from the moon are published in [2e], [3e], and [4e]. Adams et al [5e] reported Geant4 calculations of the LNA which is then compared with LP data. This spectrum from $10^{-2}$eV to 10 GeV is used to determine the background in the HEX CZT detector using Geant4. This is illustrated in fig(5.3).

*In this thesis, the HEX background is simulated using Geant4 for GCR protons and the LGRA and LNA. SEPs were not used for the calculation at this stage.*

What is of interest to the HEX experiment at this point is:
Figure 5.3: The lunar neutron albedo (LNA) simulated using Geant4 from [5e]. This spectrum ranges from $10^{-2}\text{eV}$ to 10 GeV.

- the background in the CZT detector due to secondary particles produced by GCRs and the LNA
- how it compares to the background due to LGRA
- the effectiveness of the ACD to minimize this background

The next section discusses the processes by which secondary particles are produced by GCRs.

5.2 Particle Shower Production by Galactic Cosmic Rays

When high energy GCR protons collide with a target nucleus of the spacecraft or detector material, or in the crust or atmosphere of a planet, the nucleus breaks up, producing a large number of secondary particles. These secondaries are mostly hadrons - nucleons, charged and neutral pions, K mesons, hyperons and their corresponding anti-particles. This explosive disintegration or spallation of the target nucleus imparts high energy to the resulting secondary particles, and these high energy nucleons undergo collisions with more nuclei, producing more of the above mentioned secondary particles. These are called **hadronic showers**, where one hadron interacts with a nucleus, producing more hadrons via the strong interaction. As the hadronic shower progresses, the energy
of the spallation nucleons decrease to the point that they do not produce any more secondaries, and are stopped in the material by ionization.

The fig(5.4), adapted from [9a] depicts the formation of a secondary particles due to high energy cosmic ray interaction.

The charged pions produced in the hadronic showers have a mean life of $2.6 \times 10^{-8}$ seconds, and decay by weak interaction in flight to produce charged muons.

\[
\begin{align*}
\pi^+ & \rightarrow \mu^+ + \nu_\mu \\
\pi^- & \rightarrow \mu^- + \bar{\nu}_\mu
\end{align*}
\]
The $\mu^\pm$ produced by decay of $\pi^\pm$ have a mean life of $2.19 \times 10^{-6}$ seconds, and are generated with relativistic energies because the pions decay in flight. Charged muons are also produced by the weak decay of K-mesons. Muons decay into electrons/positrons and neutrinos

$$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$$
$$\mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu$$

These high energy electrons and positrons emit photons via bremsstrahlung. Neutral pions $\pi^0$, also produced in the hadronic showers, have a very short lifetime of $10^{-16}$ seconds, decaying into two high energy $\gamma$-rays. These high energy $\gamma$-rays initiate the electronic showers by the process of pair-production. More electron-positron pairs are produced, generating photons via annihilation. The entire process continues, forming an electromagnetic shower. The shower continues till the electrons and positrons are produced with lower energies. This critical energy at which the shower is stopped ranges from $\sim 100$ MeV for air to $\sim 50$ MeV for Aluminum. These electrons and positrons slow down to rest mass energies by collisional energy losses in the material, and the positron is annihilated with the emission of two 0.511 MeV photons in opposite directions. The energy of the photons are now such that they lose energy via Compton scattering.

Neutrons and $\gamma$-rays produced in these showers are the major contributors to instrumental background, and are the main constitutes of planetary and atmospheric albedos. The next section discusses their interaction and transport in matter, and the contribution to background due to neutrons and $\gamma$-rays.

### 5.2.1 Production of background due to secondary radiation

#### 5.2.1.1 Background from neutrons

The basic concepts of neutron interaction with matter was described in section 1.1.5.2. Neutrons interact with nuclei, and are either annihilated, giving rise to secondary radiation or are scattered leading to a change in direction and/or energy. The secondary radiation produced as a result of neutron interactions are heavy charged particles and in some cases $\gamma$-rays. When energetic neutrons suffer a number of collisions with nuclei at room temperature, they are “thermalized” to this energy.

Fast neutrons are free neutrons with energies $\gtrsim 1$ MeV and are generally produced in nuclear fission reactions. They are “moderated” to thermal energies by scattering in certain media, like heavy water or graphite. Thermal neutrons are those with energies
characterized by the Boltzmann distribution, with energy 0.025 eV being the mode of the distribution at room temperature. Epithermal neutrons are those with energies from 0.025 eV to 1 eV. Thus, all neutrons with energies < 0.5 eV can be classified as slow neutrons, while those with kinetic energies > 0.5 eV are fast neutrons.

Thermal neutrons have a larger effective nuclear absorption cross section than fast neutrons, and are therefore absorbed more easily by an atomic nucleus. This results in neutron-induced reactions, such as radiative capture \((n,\gamma)\). This is neutron activation and is the ability to induce radioactivity in materials. Radiative capture is probable in all nuclides but is predominant for heavy nuclides. When a neutron is captured, it forms a compound nucleus, which de-excites by emitting one or more \(\gamma\)-rays.

The probability of neutron scattering increases with energy. The secondary radiation produced by this are recoil nuclei, which pick up a considerable amount of energy during the scattering. The neutron is moderated at each interaction site, till it gets thermalized. Inelastic scattering occurs if the energy of the neutron is sufficiently high, and when this happens, the recoil nucleus gets excited and de-excites promptly with the emission of one or more \(\gamma\)-rays characteristic of the nuclei. Absorption of neutrons by nuclei with emission of heavy charged particles (like protons and \(\alpha\) particles) is possible when the energy gained by the neutrons is sufficient to penetrate the Coulomb barrier potential of the nucleus. Sometimes, \(\gamma\)-rays are also emitted with these charged particles.

Fast neutrons can also cause spallation of nuclei, which is akin to fission; the residual nuclei are excited and de-excite by nuclear “evaporation”, emitting additional neutrons and \(\gamma\)-rays.

Transport of neutrons depend very much on the composition of the material in which they are produced. Neutrons are slowed down by elastic scattering and the amount of slowing depends on the mass of the nucleus from which the scattering takes place. The lighter the nucleus, greater is the amount of energy the neutron can lose per scatter. Absorption of neutrons with energy < 1 keV is also dependent on the nuclide, again affecting neutron transport.

### 5.2.1.2 Background from gamma-rays

The most significant physical processes that contribute to the attenuation of high energy photons are the photoelectric effect, Compton scattering and pair production, as discussed in section 1.1.5.2. The photoelectric effects dominates at low energies and high \(Z\) values, pair production dominates at high energies and high \(Z\) values, while Compton scattering is the most probable interaction process at intermediate energies (hundreds
of keV to \(~1\) MeV)) for all Z and is significant even at low Z and low energies. The nuclear photoeffect is also a means by which \(\gamma\)-rays are attenuated, but its interaction cross section is very small; only one \(\gamma\)-ray in \(10^5\) or \(10^6\) interact with nuclei, and the end product of the reaction is a neutron.

In spacecraft materials and the atmosphere or crust of planets, line and continuum \(\gamma\)-ray emission are produced by a variety of mechanisms. Natural radioactivity of elements like \(^{40}\)K, and the isotopes of the U-Th decay chains produce nuclear \(\gamma\)-ray lines. Neutron-inelastic scattering and neutron-capture reactions lead to the formation of excited nuclear states and this leads to the prompt emission of \(\gamma\)-rays characteristic of the nuclide. Continua are produced by the bremsstrahlung of energetic secondary electrons and the decay of neutral pions, which are by-products of GCR proton particle showers. \(\gamma\)-rays produced in any material by these processes are scattered by interaction with atoms and lose energy in the process. These scattered photons add to the continuum at low energies.

Therefore, the background in \(\gamma\)-ray detectors consist of a broad continuum on which are superimposed lines due to natural and induced radioactivity.

It is essential to avoid contaminating the signals of interest with detector background produced by these particles. This is achieved by shielding the detector with materials that stop these particles from entering its field of view. As discussed previously, the HEX experiment employs active shielding via anti-coincidence techniques.

The next section discusses a Geant4 application specifically designed to calculate the background detected by the HEX detector on Chandrayaan-I, and to determine the background rejection efficiency of the CsI ACD.

### 5.3 Simulation of the HEX CZT background and ACD efficiency

The aim of the section is to estimate the background of the CZT detector of the HEX experiment due to GCR protons (average solar activity), LGRA and LNA, and to determine the background rejection efficiency of the ACD.

#### 5.3.1 Geant4 Application Design

The HEX payload was modeled using Geant4, as shown in fig(3.23). All the trays were modeled according to the design, and included the CZT detector and ACD in their
respective trays. The electronics cards and components in trays 1, 3, 4, 5 and 6 were not modeled. The Chandrayaan-I spacecraft was modeled as shown in fig(5.5); the components of the spacecraft that were modeled are

- all the panels of the spacecraft, made of Aluminum
- the central cylinder, made of Aluminum, which houses the fuel tanks
- the fuel tanks made of Titanium
- the fuel and oxidizer- monomethylhydrazine and MON-3

These components are shown separately in the fig(5.6). The location of the HEX payload with respect to the spacecraft is indicated in fig(5.5).

![Geant4 model of the Chandrayaan-I spacecraft with the HEX payload. Note that the other payloads and the solar panels have not been modeled.](image)

The ACD and CZT detector responses that were modeled in chapters 3 and 4 are included in this application, with both the detectors made sensitive.
Figure 5.6: Break-down of the components of the spacecraft model - Top left: the panels of the spacecraft, on which the payloads and solar panel are mounted; Top right: the cylindrical structure at the centre of the spacecraft for housing the fuel tanks and fuel; Bottom: Fuel tanks

The physics that was used in this background calculation was verified with the results from the Apollo 15 as discussed in chapter 2 and is listed in table 2.6. The electromagnetic physics used is listed in table 2.3.

An important factor to take care for the HEX CZT background simulation is the source-detector geometry. The next sections discuss the approximations and computations undertaken to determine the source-detector geometry for the cases of background simulation using Geant4.

5.3.2 Source geometries for lunar albedos

The lunar gamma-ray and neutron albedo radiations are incident from the surface of the Moon and travel upwards to strike the spacecraft and instrument. Consider the
schematic on the left hand side of fig(5.7); here, S indicates the position of the spacecraft with respect to the Moon, and H is the height of its orbit, which is 100 km. As can be seen, at any instant the radiation that strikes S comes from within the region marked between points A and B. These are the positions on the Moon where the tangents drawn from S touch the surface. In order to determine the length of the arc AB, one must make use of the radius of the Moon, R and the orbital altitude H to compute the angle \( \Phi \) subtended by AB at the centre of the Moon. Using the formula

\[ L = R\Phi \]  

one can calculate the length L of the arc AB. In order to compute \( \Phi \), consider the schematic on the right hand side of fig(5.7), and more specifically, the right angled triangle \( \triangle SAO \), where

\[
\begin{align*}
\angle SAO &= 90^\circ \\
AO &= R = 1738 \text{ km} \\
SO &= SM + MO = H + R = 1838 \text{ km}
\end{align*}
\]

The unknowns are

\[
\begin{align*}
\angle ASO &= \frac{\Theta}{2} \\
\angle SOA &= \frac{\Phi}{2}
\end{align*}
\]

and

\[ \Phi = 180^\circ - \Theta \]  

Using trigonometry,

\[
\frac{\Theta}{2} = \sin^{-1} \frac{AO}{SO} = \sin^{-1} \frac{1738}{1838} = 71^\circ
\]

and therefore, \( \Theta \) is 142°; substituting this value in eqn(5.4), \( \Phi \) is 38°. Converting this from degrees to radians and using eqn(5.3), the length L of the arc AB was computed to be 1152 km. Thus, the region of the Moon which irradiates the spacecraft can be assumed to be bound within a square of sides 1152 km in length.

For an experiment with time constraints like HEX, it is impractical to run a Geant4 simulation using the actual values of L and H. In such a situation a few approximations were made.
First the dimensions were scaled down from kilometers to meters. Then, the ratio between \( L \) and \( H \) was used to resize the distance of the spacecraft from the source and the area of the irradiating square. For practical purposes, the smallest possible distance between the spacecraft and source was selected with the criterion that the source generator was large enough to irradiate the entire spacecraft, while maintaining the ratio between the two.

The next step is to compute the equivalent integration time \( T \) the LGRA and LNA using eqn(2.7) for this source-detector geometry. Using the same methodology outlined in section 2.5, for each radiation source with integral flux \( \dot{I}(E) \), one determines the number of particles \( N \) collected in a vacuum counter of area \( A \) corresponding to \( N_0 \) primary incident particles. The integral flux of the LGRA and LNA have been computed by fitting the spectra in fig(5.2) and fig(5.3) to functions using the least-square fitting method (using piece-wise functions in energy wherever necessary), and then integrating over the valid energy range. For each case,

- **Lunar Gamma-ray Albedo**
  
  \[
  N_0 = 10^8 \\
  \dot{I}(E) = 1.008 \text{ photons cm}^{-2}\text{s}^{-1} \\
  N = 153257 \\
  A = 144 \text{ cm}^2 \text{ (area of detector)}
  \]

  \[
  T = \frac{N}{A \dot{I}(E)} = \frac{153257}{1.008 \times 144} = 1056 \text{ seconds}
  \]
Given the $10^8$ incident particles and the spectrum, this translates to an equivalent integration time of 1056 seconds.

- **Lunar Neutron Albedo**

  $N_0 = 10^8$

  $I'(E) = 10.3$ neutrons cm$^{-2}$s$^{-1}$

  $N = 293942$

  $A = 144$ cm$^2$ (area of detector)

\[
T = \frac{N}{A I'(E)}
= \frac{293942}{10.3 \times 144}
= 198 \text{ seconds}
\]

Given the $10^8$ incident particles and the spectrum, this translates to an equivalent integration time of 198 seconds.

### 5.3.3 Galactic Cosmic Ray Protons

GCR protons are isotropic in space and in principle, should bombard the spacecraft from all directions. But considering the geometry of the spacecraft-Moon as shown in fig(5.8), the Moon shades the spacecraft from GCR protons that come from below. From this it can be seen that the source geometry can be modeled as a hemisphere. Using GSPM, the source geometry for GCR protons was made a hemisphere with radius 2.5

![Figure 5.8: GCR proton source geometry with respect to the moon and spacecraft.](image)
m, centered at the origin of the co-ordinate system, where the centre of the spacecraft model was also located. Using eqn(2.7), one can compute the integration time with respect to the source geometry and the integral flux of the GCR protons for average solar activity. This is given as,

- \( N_0 = 10^8 \)
- \( \dot{I}(E) = 3.14 \text{protons cm}^{-2}\text{s}^{-1} \)
- \( N = 66162 \)
- \( A = 144 \text{cm}^2 \) (area of detector)

\[
T = \frac{N}{A \dot{I}(E)} = \frac{66162}{3.14 \times 144} = 146 \text{ seconds}
\]

Given the \( 10^8 \) incident particles and the spectrum, this translates to an equivalent integration time of 146 seconds.

### 5.3.4 Simulation Results

For each of the three cases; LGRA, LNA, and the GCR protons for average solar activity, the Geant4 application to simulate the HEX CZT detector background, and suppression by ACD was executed. The output of each the simulations were

- total energy deposit in the CZT detector
- background suppressed energy deposit in the CZT detector
- the ACD four window counts

The energy deposit spectra were normalized with respect to the area of the detector, the integration time as computed above, and the size of the energy binning.

The spectra shown in fig(5.9) have been simulated assuming that the spacecraft is stationary over the region defined by the source in GSPM. The contribution to the total detector energy deposit by the GCR protons are represented by the closed circles, while the open squares and blue asterisks correspond to the LNA and LGRA respectively. As can be seen the maximum contribution comes from the GCR protons, while the LGRA contributes the least; the numbers are tabulated in table(5.1)
Figure 5.9: The total CZT background is represented by the solid red line, while the different components that contribute to this background are shown; the closed circles represent the contribution due to GCR protons, the open squares represent the contribution due to LNA, and the blue asterisks represent the contribution due to the LGRA.

<table>
<thead>
<tr>
<th>Component</th>
<th>Percentage contribution</th>
</tr>
</thead>
<tbody>
<tr>
<td>LGRA</td>
<td>8%</td>
</tr>
<tr>
<td>LNA</td>
<td>31%</td>
</tr>
<tr>
<td>GCR</td>
<td>61%</td>
</tr>
</tbody>
</table>

Table 5.1: Table summarizing the percentage contribution of the lunar albedos and the GCR protons to the energy deposit in the HEX CZT detector, assuming that the spacecraft is stationary over the region defined by the source.
These results show that the locally produced secondaries due to interactions of GCR protons with the material surrounding the detector contributes most to the simulated CZT background.

Fig(5.10) shows the total modeled CZT background and the background after veto rejection. The predicted veto efficiency of the ACD over the entire energy range is 21%.

When one considers veto efficiency for each of the three components individually as listed in table(5.2), it appears that the ACD is most effective in suppressing events due to the GCR protons. As discussed earlier, these protons are incident on the back and sides of the spacecraft, so the secondary flux that they generate when they interact with the spacecraft, fuel and fuel tanks, have to pass through the CsI ACD before they reach the CZT. This sort of suppression by the ACD is an out-to-in process; this means that unlike the Compton scattered photons, these events come from outside the CZT and are stopped by the shielding placed below it. The ACD veto efficiency due to the LGRA is a pure in-to-out effect; this means that this is due to Compton scattering that occurs from the CZT into the ACD. This is evident from the fact that the veto efficiency of
the ACD due to LGRA photons is similar to the CSE computed for the 1 cm thick CsI ACD (refer chapter 3).

<table>
<thead>
<tr>
<th>Component</th>
<th>ACD veto efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>LGRA</td>
<td>11%</td>
</tr>
<tr>
<td>LNA</td>
<td>13%</td>
</tr>
<tr>
<td>GCR</td>
<td>37%</td>
</tr>
</tbody>
</table>

Table 5.2: Table summarizing the ACD veto efficiency for each of the three components that contribute to energy deposit in the HEX CZT.

Finally, the table (5.3) gives the count rate of the four ACD windows in units of counts per minute, due to the three components that contribute to the total background; the error due to counting statistics is also given. The energy range spanned by each window is indicated in the table. These results are depicted by way of a graph in fig(5.11) as a four window or ‘four-channel’ spectrum; it appears that for all three components of the background radiation, Window 2 (170-250 keV) has the highest count rate, while the GCR protons cause most of the energy deposition in the ACD. Thus, from the simulation results, Window 2 can be selected during flight as that window with the most efficient veto action.

5.3.5 Relevance of simulation results for HEX

The simulation of the HEX background using Geant4 is a composite work that started with the validation of different aspects that would be used as input to the simulation, and included modeling the response of the two detectors of the HEX instrument. All these steps culminated with the estimation of a revised background computation for HEX in the lunar environment. Further work that can be done with respect to this are as follows:

1. include energetic solar protons and electrons in the list of sources that contribute to the background, for different stages of solar activity
Chapter 5. The HEX background simulation

Figure 5.11: Simulated four-channel ACD spectrum due to the lunar albedos and the GCR protons; the closed circles correspond to the contribution due to the GCR protons, the asterisks indicate the contribution due to the LNA, while the open squares represent the contribution due to the LGRA. The y-axis is in logarithmic scale.

2. the background due to the variation of lunar albedos and the GCR protons change with solar activity

3. the background due to different lunar terrains

This revised background calculation, and the predicted veto efficiency of the ACD can be used to compute line sensitivities for the $\gamma$-rays that lie within energy range of interest of the HEX CZT detector according to eqn(1.12).

Simulating the ACD four-channel spectrum, one can study the energy deposits due to the different components that contribute to detector background in the lunar environment, and can be used to

1. predict the temporal variation of the four channel spectrum, say with respect to variation with solar activity

2. correlate the count rate in the four channel with occurrence of energetic events

3. to determine the component of background radiation that contributes most to the energy deposit; this helps in selection of the window with the most efficient veto action.
Bibliography


