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Geant4 Simulations And Modeling For Space Radiation Environment

Kavita Lalwani[1*], Amit Yadav[2]

[1*]Department of Physics, Malaviya National Institute of Technology Jaipur, India
[2]Department of Electronics and Communication Engineering, RBS Engineering Technical Campus Agra, India

[*]**Corresponding author:** Kavita Lalwani
kavita.phy@mnit.ac.in

Abstract
The space radiation environment consisting of charged particles (electron and proton) and heavy ions gives a significant challenge to future space travels. Future space missions will rely more on accurate simulations of radiation transport in space through spacecraft to predict astronaut dose and energy deposition within spacecraft electronics. In order to accurately understand the space radiation environment, mostly Galactic Cosmic Radiations, Solar particle events and Trapped particles, fast simulations based on Monte Carlo methods are required. In this work, a systematic simulation study of modeling the space radiation environment is carried out. The radiation flux and radiation dose are measured using Geant4 simulations.

Keywords: Geant4 Simulations, Galactic Cosmic Rays, Solar Particle Events, Trapped Particles, Energy loss by proton, heavy ions, Space radiation environment.

Introduction

Space radiation environment has three main components: galactic cosmic rays (GCR), trapped particles and solar energetic particles (SEPs). Solar particles and GCR consists of protons with a small mixture of helium ions, and even smaller composition of heavier charge particles. The trapped particles contain primarily electrons and protons in closed orbits by the Earth's magnetic field. While Solar energetic particles events (SEPs) are sporadic, the particles' energy distribution and high flux are of major concerns. Figure 1 shows the sketch of the Space Radiation Environment. The relative importance of the components of the space radiation environment is considered for contributions to the radiation risk to systems deployed in the space environment. The environment in a space vehicle is characterized by the primary radiation field consisting of various high-energy charged particles from protons up to heavy ions such as ^{56}Fe or even higher 'Z' values, and by radiation components of photons, electrons, neutrons, and other reaction products from the interaction of primary particles with the materials of the object. This results in many different types of radiation together with broad energy distributions up to particle energies of many GeV/n. All these radiations from different sources and their interactions by various mechanisms determine the actual field of ionizing radiation at any given time and location within the heliosphere. No real physical system is able to measure the dosimetric quantities directly. These quantities are defined for radiation protection as the energy deposited by radiation on the atomic composition of the irradiated materials. In this work, simulations and modeling of the space radiation environment is carried out at fixed solar modulation as well as at variable solar modulation potentials using Geant4 simulations **[1].** Further, the energy loss and radiation doses by space radiation are carried out and presented, which are needed to aid in prediction of radiation risks in space for safety of electronic equipment and other systems.

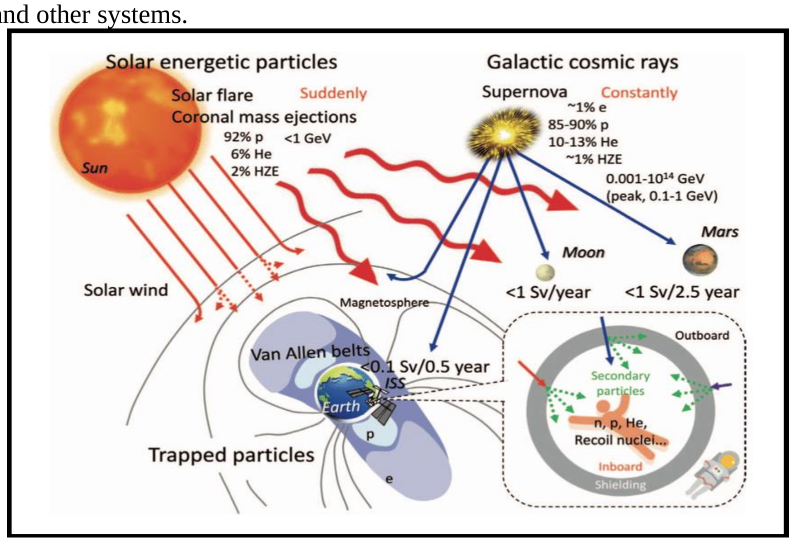

Fig 1: Sketch of Space Radiation Environment.

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In this work, following important activities have been carried out:

- Transport code for space radiation environment model with definition of GCR environment.
- Investigation of physics interactions of radiations in the space radiation environment.
- Perform dose estimates inside the specified object during simulated GCR and solar energetic particle events.

Geant4 Simulations for Space Radiation Environment

In this section, complete process steps, which are used to simulate and model the space radiation environment using the simulation software tool Geant4 [1] and ROOT [2], developed by CERN laboratory, are discussed as shown in the flowchart (Figure 2). GEANT4 supports multithreading and MPI, allowing for fast distributive simulations with high-performance computing clusters through computational simulations.

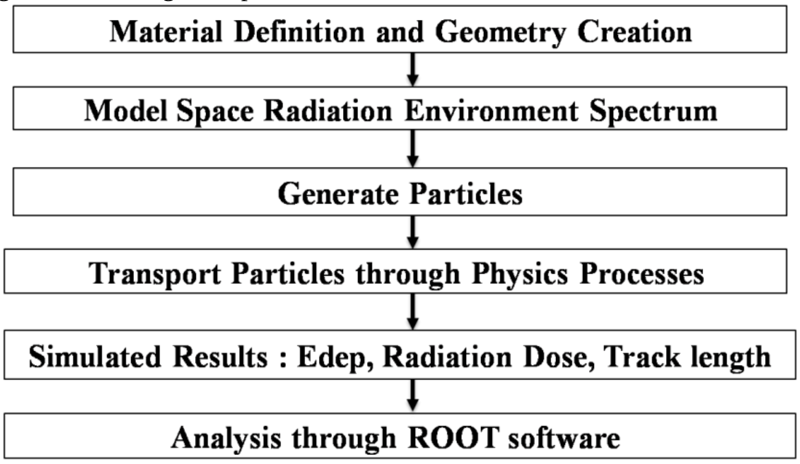

Figure 2: Flowchart of Simulation and Modeling for Space Radiation Environment in Geant4 framework.

In the following sections, a systematic study to develop the radiation model for the GCR environment is presented. The Radiation Model in GCR environment is expressed through following equations (1, 2) **[3],**

$$j_{lis}(E) = j_0 \beta^{\delta} (E + E_0)^{-\gamma} \quad ......(1)$$

$$J_i(T,\phi) = J_{LIS,i}(T + \Phi_i)\frac{(T)(T + 2T_r)}{(T + \Phi_i)(T + \Phi_i + 2T_r)} \quad .....(2)$$

where T is the particle's kinetic energy per nucleon, Φ(i)= φ(i) (eZ_i/A_i) T_r = 0.938 GeV/nucleon. The only temporal variable here is the modulation potential Φ(i), which is related to solar activity and parameterizes the shape of the modulated spectrum. The development of radiation model is carried out in following two phases systematically as shown in flowchart (Figure 3):

Phase I: Radiation Model for fixed solar modulation potential: Equations (1, 2) are implemented in the algorithm using ROOT software in C++ and random number for energy is generated for corresponding to each ion in GCR spectrum for fixed solar modulation potential (solar minimum (400MV) and solar maximum (1500 MV)). The LIS parameters for given solar modulation potential are taken from reference [3].

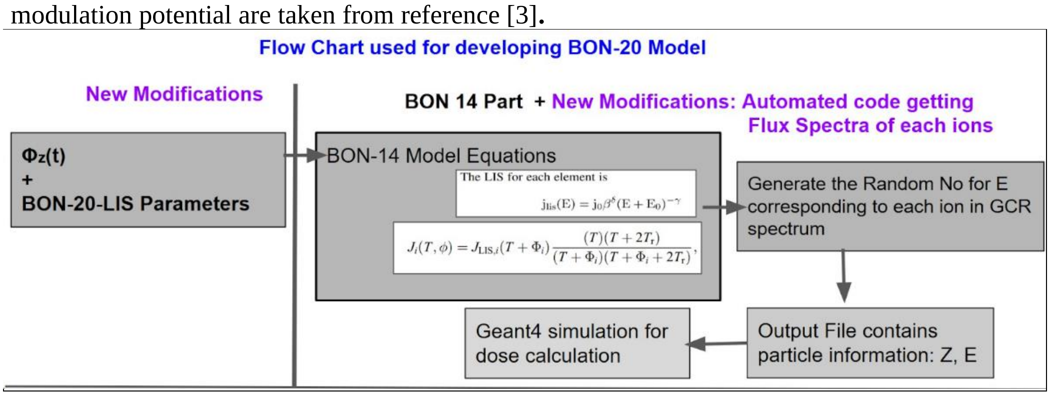

Figure 3: Flowchart for Space Radiation Model at Fixed and variable solar modulation potential.

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Phase II: Radiation Model for variable solar modulation potential:
In the phase of developing the Radiation Model, variable modulation potential is determined by writing it as a function of time for each ion and it is defined as,

$$\phi_Z(t) \equiv \phi_{fit}[F_{\mathrm{ACE}}(t,Z);a_Z,b_Z] = \left[a_Z - b_Z \cdot \ln F_{\mathrm{ACE}}(t,Z)\right]^2 \quad .....(3)$$

The radiation flux is generated for various ions at variable solar modulation using ROOT, and results are shown in Figure 4. The generated model of the space radiation environment is fed into the Geant4 to generate the particles and perform the simulations.

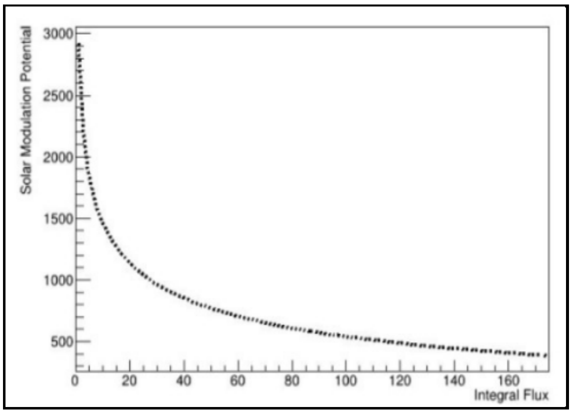

Figure 4: Generated flux of GCR for variable solar modulation potential in ROOT.

Equations (1,2) are implemented in the algorithm using ROOT software in C++ and random number for energy is generated corresponding to each ion in the GCR spectrum. The LIS parameters for variable modulation potential are taken from reference [4]. After implementing the radiation model for space radiation environment, the physics list & Model (QGSP_BIC_HP) is prepared, which define the interactions of charged particles with detector material in Geant4 framework, which consists of Binary cascade, precompound and various de-excitation model for hadrons 'along with high precision neutron model used for neutrons below 20 MeV. Further, to simulate the radiation dose profile, Stepping action class is used in Geant4 and particles are categorized based on various quantum numbers in particle physics, such as lepton number, baryon number, weights and particle id codes etc as shown in flowchart (Figure 5). Then accordingly the radiation doses are measured for different particle radiations using the algorithm developed in the Geant4 framework and results are discussed in the following sections.

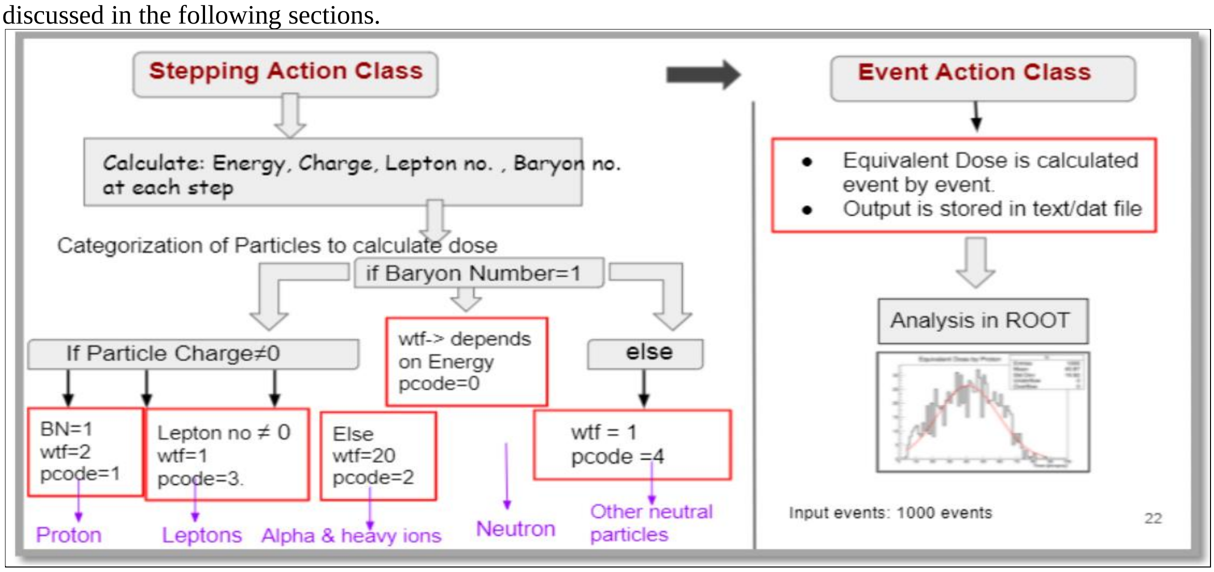

Figure 5: Flowchart for simulating the radiation dose profile in Geant4 framework.

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Results

In this section, results on the differential radiation flux and radiation dose by various particles/ radiations are presented. Figure 6 shows the differential flux for ^{2}He (left) and oxygen (right) at solar minimum (400MV) and at solar maximum (1500MV).

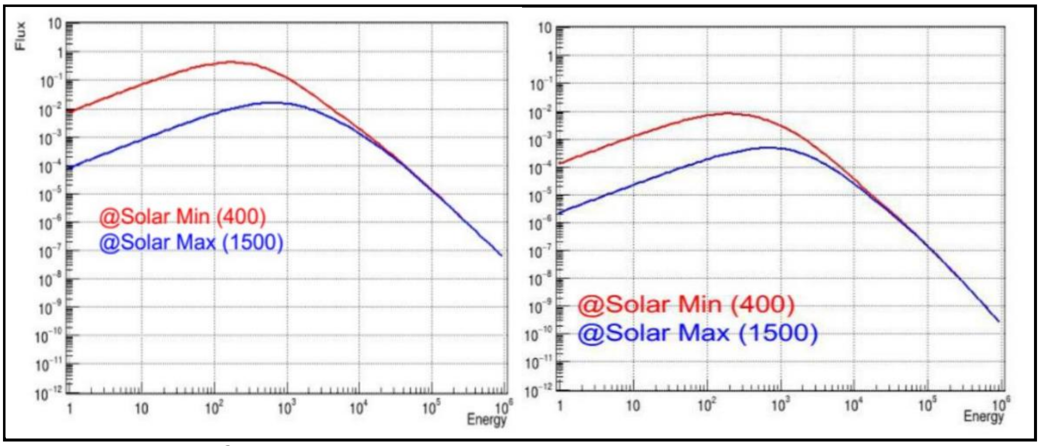

Figure 6: Differential flux for ^{2}He (left) and oxygen (right) at solar minimum (400MV) with red colour and at solar maximum (1500MV) with blue colour.

The differential flux for Z= 10 (left) and Z = 8 (right) are shown in Figure 7.

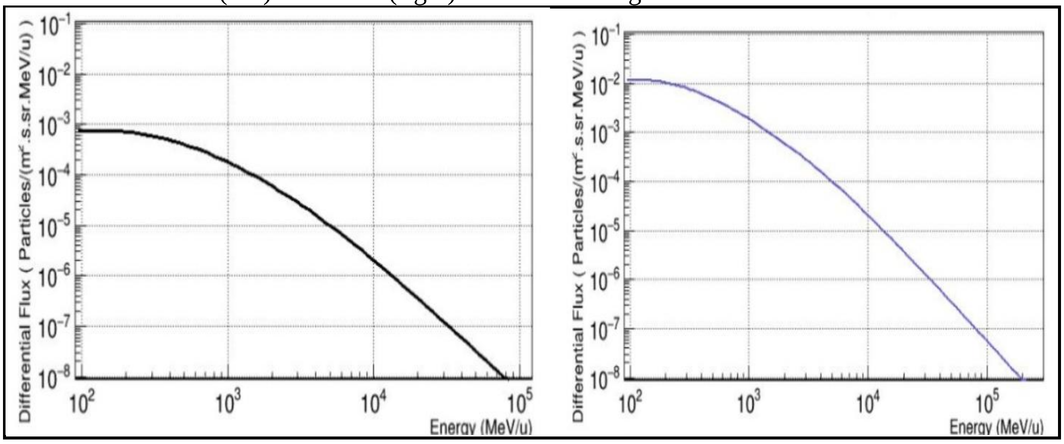

Figure 7: Differential flux for Z = 10 (left) and Z= 8 (right) for variable potential.

Further, to simulate the radiation dose profile, the slab geometries of Al and water with different dimensions are created and visualized in Geant4, as shown in Figure 8. The Slab 1 & 3 are created with aluminium of volume density of 2.700g/cm^{3} having dimensions of 7.407cm in length, 1 cm in width and 0.135 cm in height. The slab 2 is created, which is filled with water of volume density of 1g/cm^{3} having the dimensions of 0.3mm in length, 1 cm in width and 0.135cm in height.

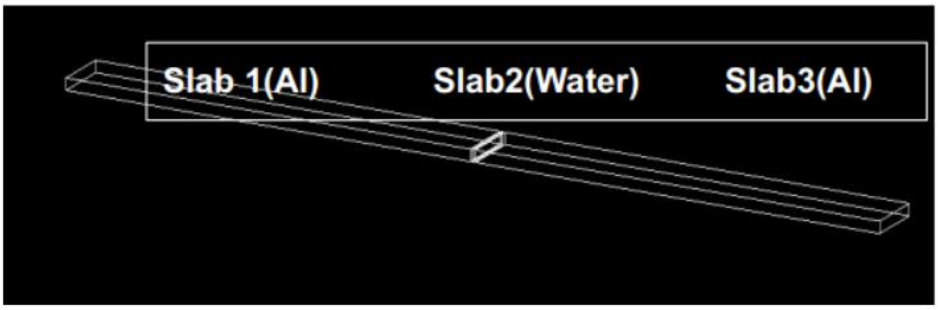

Figure 8: Geometry consisting of slab 1 & slab 3 filled with aluminum, and slab 2 with water.

We have produced GCR particle spectrum through GPS (Gun Particle Source class of Geant4).

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The energy loss is determined in the Aluminum shield slab using Stepping Action Class in Geant4.
The variable shielding thickness of Al: 10g/cm^2, 20g/cm^2, 30g/cm^2, 40g/cm^2. The absorbed dose is determined from energy loss by dividing it from detector mass (dE/dm). As the absorbed dose is determined as a function of the particle's kinetic energy, therefore the sum of the absorbed dose spectrum is performed at each depth in Al slab. Figure 9 shows the equivalent dose in Aluminium slab. The obtained results are compared with other simulation software tools as shown in Figure 9. Our results are in agreement with MCNP and PHITS [5].

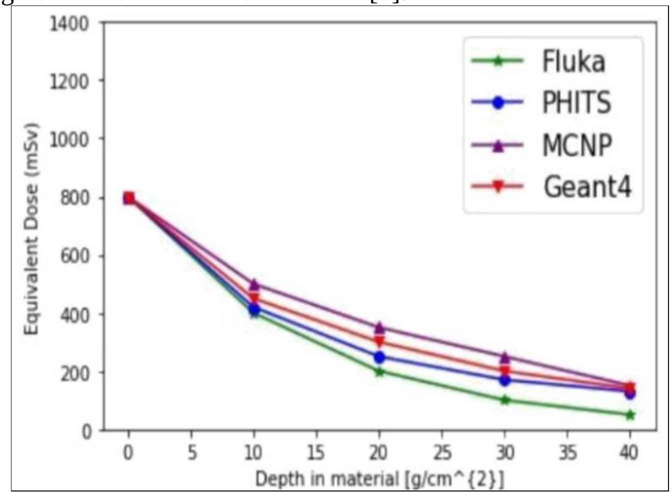

Figure 9: Equivalent Dose as a function of Al depth.

Acknowledgements
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