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Simulation of cosmic rays interaction with simple human eye model by FLUKA and GEANT4 packages

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In the last several decades, astronauts on space missions experienced a phenomenon known as light flashes. Results of experiments conducted, not only by crews aboard MIR and ISS, show that this phenomenon is a consequence of the interaction of cosmic rays with the human visual system. The results discussed in our paper were obtained by simulating the interactions of high-energy protons originating from cosmic rays with a simple human eye model. These simulations have been performed by two advanced Monte Carlo simulation packages - FLUKA and GEANT4 - configured for the same conditions. Presented yield functions for different secondary particles created inside the eye are products of the simulated interactions. Contribution of the Cherenkov photons was also taken into account. The article briefly discusses the possibility of the creation of light flashes by the observed secondary particles.

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1. Introduction

The light flashes occur when these particles pass through the vitreous humor of the eye, which is the gel-like substance that fills the eyeball. As the high-energy particles move through the vitreous humor, they ionize the atoms and molecules in their path. This ionization process releases photons of visible light. The flashes are perceived by the astronaut or observer as brief, random bursts of light, similar to seeing a small, quick flash. The flashes can vary in intensity, duration, and color. They can appear as white, blue, green, or red flashes, depending on the energy and type of particle involved in the interaction.

While the exact mechanism behind the perception of light flashes by the human eye is not yet fully understood, ongoing research and observations continue to shed light on this fascinating phenomenon.

During the first missions to the moon, astronauts on Apollo mission saw above mentioned phenomenon of LF. Later, through the missions of Apollo 16 and 17, the ALFMED experiment confirmed that these LF consist of high-energy particles. ALFMED was later replaced by experiments SILEYE 1 and 2, installed on the MIR station. These experiments still continue on ISS, first as Alteino-Sileye 3 and then as an ALTEA program. The methodology of this experiments relied on using a helmet with a particle detector on the head of the astronaut and a type of handheld button triggered in the instance of the LF occurrence.

The ALFMED experiment results were primarily reports for NASA [1]. However, the SILEYE experiment published multiple papers about this matter, such as [2] or [3]. Similarly, the ALTEA program had various articles explaining the purpose and results, [4] or [5].

The first results of these experiments ([1]) presented a hypothesis that the light flashes are made either by:

- the interaction of high-energy particles with the material of the human eye, causing Cherenkov radiation
- direct interaction of particles with retinal cells or optic nerve.

Later papers mention two separate components of cosmic rays as the cause of these light flashes ([3]), namely:

- heavy nuclei
- protons

Therefore, this indicates two complementary mechanisms for the origin of light flashes. However, as suggested by [6], concrete mechanisms are still a mystery.

2. Models of the human eye

One of the possible origins of light flashes are high-energy protons from cosmic rays. Therefore, our model at this level of the study injects protons of various energy levels into the simple model of the human eye. The early stages of the LFs model include a simple model of the human eye, which can later evolve into more elaborate simulations. Currently, we use two packages for our simulations: GEANT4 [7, 8] and FLUKA [9]. We have selected these two packages because they are currently the most extensive particle interaction simulation toolkits. GEANT4 is probably the most well-rounded comprehensive toolkit for simulations. FLUKA, due to its almost unique capability for simulating hadronic interactions, including low energy neutron transport is the baseline Monte Carlo code for the radiation environment simulations. It has a full treatment of low and high energy nuclear, hadronic, and electromagnetic phenomena, however, special emphasis has been put on the effects occurring around energies of a few GeV and below. In both simulation frameworks we used the geometry of a block of water 2 cm wide, 3 cm long, and 2 cm high, which represents the human eye. Protons came from one direction, simulating the direction from which the light hits the retina.

2.1 Simple model in GEANT4

The GEANT4 package gives information about particles created during the interaction, such as the type of the particle, its kinetic energy, dose, or data about its trajectory at any given time point. GEANT4 is a free package used to simulate the interaction of particles with matter. Two independent organizations started developing a toolkit with these properties (CERN and KEK). The two attempts merged into one in 1994 to create new object-oriented software. The GEANT4 package includes basic examples for beginners to explain how to operate the software [10]. One of the beginner examples (example B1) serves as a base of the LFs GEANT4 model. It is a block 2 cm wide, 3 cm long, and 2 cm high, filled with water (see Figure 1). Upon initialization, the high-energy protons flow through the water block along the z-axis.

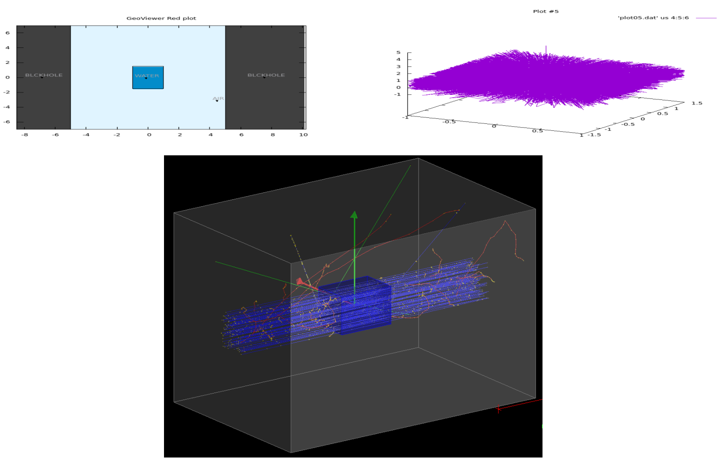

Figure 1: The LFs model - FLUKA geometry vs. GEANT4 geometry

We use several inherent classes of GEANT4 that help us build our construct. The most important one is Physics List. This class determines what types of interactions are being considered by the simulation. In our case, we use a physics list named *QGSP_BIC _HP_EMZ*, recommended for medical applications [11]. It includes the Quark-Gluon String model (QGS), the FRITIOF String model (FTF), the *G4Precompund* model used for de-excitation (P), the Binary Cascade model (BIC), the High Precision neutron model (HP), and the Electromagnetic physics constructors option 4 (EMZ) [11]. The second most important would be the *G4ParticleTable* and *G4ParticleGun*, which

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define the injected particles, and describe their momentum, direction, and energy, respectively. Our simulation uses various energies for injected protons, specifically 1, 10, and 100 MeV, and 0.5, 1, 2, and 10 GeV. The number of particles released into the block is 10 000 protons. For each input energy, we get information about the trajectory of the particles (either primary or secondary), the type of the particles, their energy, absorbed dose, and others. This information allows us to reconstruct the spectra for each type of the created particle. The best outcome would have been the creation of optical photons inside the water block.

2.2 Simple model in FLUKA

The second package used in our simulations is FLUKA. Historically, three generations of FLUKA can be distinguished, the FLUKA of the '70s, the FLUKA of the '80s, and the modern FLUKA, distributed by CERN and INFN (2003 - 2019) or by CERN only (from 2020) [12]. FLUKA functions based on the use of so-called cards. Every action has its card. A crucial part of the FLUKA is also its strict input alignment. The script's format is not unrestrained unless specified at the beginning [12]. Presently, there exist several tools modelling the geometry for FLUKA, among them we have used FLAIR [13]. It can be used to build the input in more general way and during post processing the output of the code.

Similarly to GEANT4, the initial model is straightforward. We define three regions using cards *RectanguarParallelepiped* (or *RPP*) and *REGION*. The first one is called a blackhole, an obligatory part of the geometry in FLUKA [12]. The second region is a block of air (10 x 15 x 10 cm). And the last one is the water block with identical dimensions to the one in GEANT4.

The high-energy protons travel along the z-axis, as defined by the card *BEAMPOS*. Similar to GEANT4, we use different energies for protons. The simulation will run first with 10000 protons and later with increased statistics (100000 p^+). The simulation provides information about the types of particles created, their energy, track, total absorbed dose, and more [13].

All simulations have been divided into several independent batches of equal size. These have been used to estimate the statistical errors arising from fluctuations in the event sampling and during cascade simulation. However, systematic errors seem to be more important. They arise from uncertainties in the cascade development and from extrapolation of existing data. The accuracy of the cascade simulation is affected by approximations in geometry and material description, incompleteness of physics models and cross section data sets. To assess the accuracy of FLUKA results in well-defined geometries with known material composition, FLUKA has been bench-marked in several small scale experiments using neutron counters and activation foils. The agreement with measurements is of the order of few tens of percent.

3. Results

The simulation uses specific energy level of protons, namely: 1 MeV, 10 MeV, 100 MeV, 0.5 GeV, 1 GeV, 2 GeV and 10 GeV. From the gained data, we can plot spectra for the created particles or differentiate what types of secondary particles are formed during the simulation. The data acquired from simulations are sorted by the type of secondary particle created. The required information is then recorded separately for analysis. From this reduced data, we plot various histograms. The results from simulations in FLUKA can provide us with several different types of data. The particle fluences and energy depositions have been obtained by using a track length estimator in the defined detector layer - eye

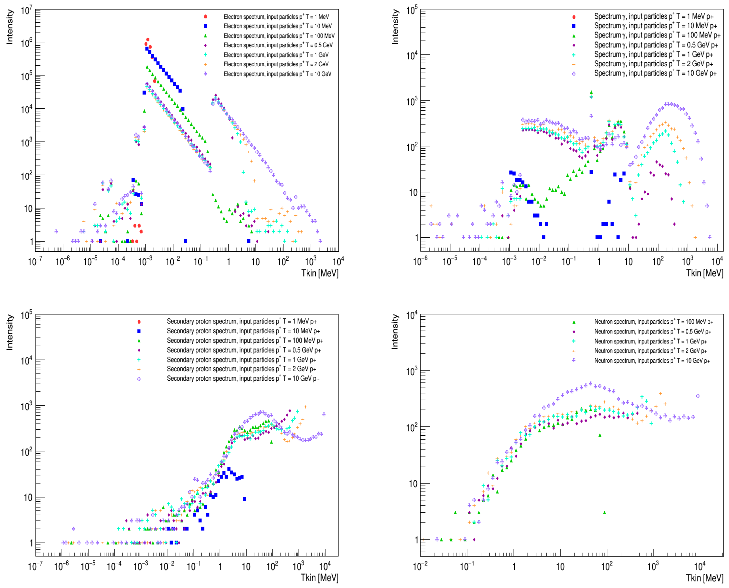

Figure 2: Electron (upper left), gamma (upper right), secondary proton (bottom left) and neutron (bottom right) spectra for various energy levels of primary protons.

We can see in Figure 2 the spectra of electrons, gamma, secondary protons and neutrons created during the interaction of protons of varying energies with our simple model. The secondary particle with the most abundance was the electron. Other particles recorded were for example, secondary protons, gamma particles, neutrons, alfa particles, or pions. On the following histograms, you can see different particles and their intensities. FLUKA can be used to generate and propagate optical photons of Cherenkov, scintillation and transition radiation light. Light generation is switched off by default and is activated and fully controlled by the user by means of data cards and user routines. This is true also for the optical properties of materials. These include the refraction index as a function of wave-length (or frequency or energy), the reflection coefficient of a given material, etc. [12]. We have simulated all these possibilities, but due to lack of space we present only the results with Cherenkov photons option. The scoring quantities of interest were defined on a region-independent RZ geometrical mesh encompassing the whole detector - eye, with individual bins z cm in Z , R cm in R and extending over the full azimuthal angle. The almost full symmetry of the detector around its axis allows for acquiring a precise spatial distribution of activity. Simultaneously, bins are large enough to provide good statistics. The maps above describing the scoring, have been obtained from the raw data by post processing using the FLAIR [13] tool and are shown in Figure 3. The energy deposition maps (in GeV) for a vertical cut through the eye in $R - Z$ binning are presented there in the top part, for 100MeV and 10GeV primary protons. In the same way the maps of charged hadron and optical photons fluences can be seen in Figure 3 in the middle and bottom part. Fluences are expressed in cm^{-2}.

The spectra of dominant particle production are shown in Figure 4.

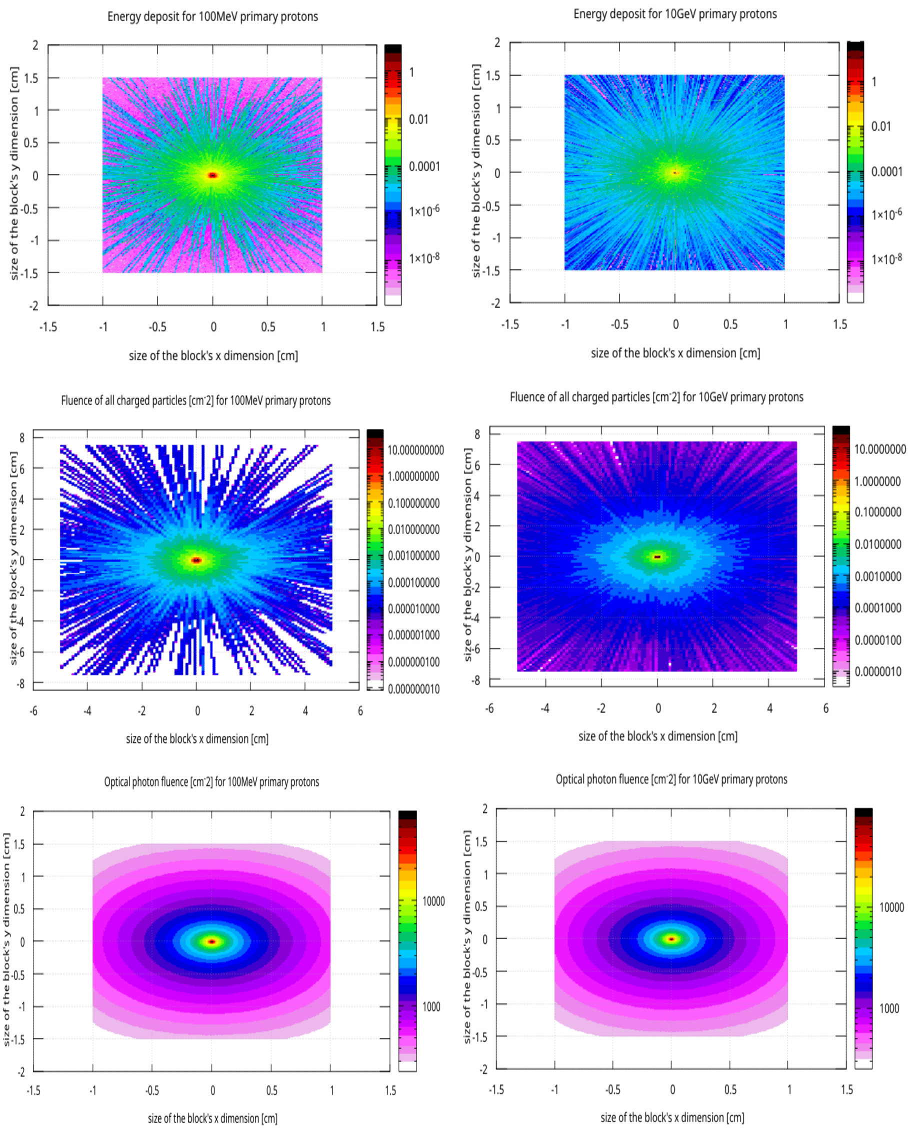

Figure 3: Energy deposition, charged hadrons an optical photons fluence maps in the cross section of the region representing the eye

4. Conclusions

The interaction of high-energy protons with water in our simple model of the human eye created many secondary particles, from electrons, pions, neutrons, secondary protons up to oxygen or iron and their isotopes. In GEANT4 simulations, the histograms obtained from simulation data show yield functions for different secondary particles. These specific particles were the most abundant of all secondary particles. The γ spectrum in Figure 2 displays spectra of created γ particles for each initial energy of injected protons. Even if the amount of the particles is in the hundreds or thousands we can not distinguish visible photons.

On the other hand in the FLUKA simulations we can see non-zero optical photons fluence

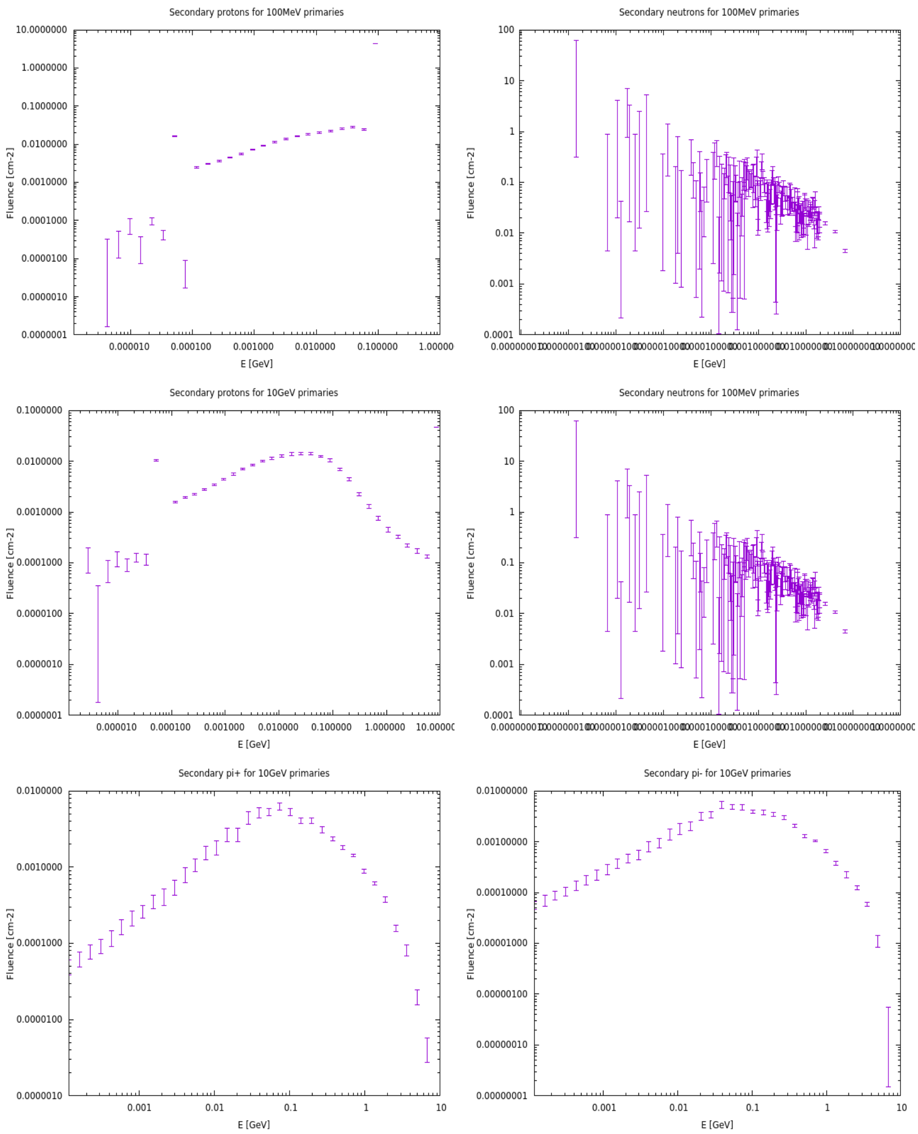

Figure 4: Secondary proton and neutron spectra at 100 MeV and 10GeV, while nonzero pion spectra only at 10GeV of primary protons

maps for primary protons energies at 100 MeV and higher. For lower energies there were no optical photons scored. As to the spectra of secondary particles from FLUKA simulations (Figure 4) they are absolutely dominated by protons and neutrons at lower energies unlike to GEANT4 data (Figure 2). However, obtaining the same result in GEANT4 is not straightforward. Although the simulation inputs and conditions that were used in GEANT4 resp. FLUKA were approximately the same, their outputs can not be compared presently, as they were obtained in respective different ways as commonly used in above mentioned frameworks. In the future, it would be most important to obtain results from both codes in the same way and format, most probably in ROOT format. It will also be necessary to use various primary beams and to vary materials that surround the are around the eye by including at least vacuum.

5. Acknowledgment

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References

[1] NASA, *Apollo program summary report*, .

[2] V. Bidoli, M. Casolino, M.P. De Pascale, G. Furano, A. Morselli, L. Narici et al., *Study of cosmic rays and light flashes on board space station mir: The sileye experiment*, Advances in Space Research **25** (2000) 2075.

[3] M.C. et al., *Dual origins of light flashes seen in space*, Nature **422** (2003) 680.

[4] L. Narici, V. Bidoli, M. Casolino, M.P. De Pascale, G. Furano, A. Morselli et al., *Altea: Anomalous long term effects in astronauts. a probe on the influence of cosmic radiation and microgravity on the central nervous system during long flights.*, Advances in Space Research **31** (2003) 141.

[5] L.D. Fino, F. Agostini, M. Larosa, L. Narici and V. Zaconte, *The altea experiment onboard the international space station*, Journal of Physics: Conference Series **383** (2012) .

[6] W.G. Sannita, L. Narici and P. Picozza, *Positive visual phenomena in space: A scientific case and a safety issue in space travel*, Vision Research **46** (2006) 2159–2165.

[7] J.A.e.a. J. Allison, K. Amako, *Geant4 developments and applications*, *Vision Research* **53** (2006) 270.

[8] G. Collaboration, *Geant4: Book for application developers, release 10.7*, .

[9] S.R.e.a. A. Fassò, A. Ferrari, *The physics models of fluka; status and recent developments*, in *Computing in High Energy and Nuclear Physics 2003 Coference (CHE2003)*, (USA), 2003.

[10] G. Collab., *Introduction to geant4*, 2022.

[11] M. Novak, *Short guide to choosing your physics lists*, .

[12] CERN, *FLUKA manual*. CERN, 2020.

[13] V.Vlachoudis, *Flair: A powerful but user friendly graphical interface for fluka*, in *Proceedings of theInt. Conf. on Mathematics, Computational Methods and Reactor Physics (MC 2009)*, (Saratoga Springs, New York), 2009.

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