

# The Cosmic Particle Rain - User's Manual

P. G. Isar<sup>1</sup> and D. Hîrneă<sup>1</sup>

<sup>1</sup> Institute of Space Science, Magurele, Bucharest, Romania

**Abstract**—For more than a 100 years we know about the existence of some very mysterious particles, highly energetic, known as cosmic rays. They reach at the top of Earth's atmosphere, coming from space and interact with air molecules generating billions of elementary particles. These events are called by scientists Extensive Air Showers (EASs). The Pierre Auger Observatory is the largest EAS detector in the world [1]. It's mission is to detect and study the most energetic cosmic rays, known as the ultra high energy cosmic rays. These outstanding particles have energies billions times greater than what humans can achieve in laboratories using particle accelerators. Which and where are the sources of these particles? Somewhere outside of our galaxy but we still don't know them exactly [2]. Our application is designed to offer an intuitive view over the development of an EAS induced by a cosmic ray, followed by the response of simplified versions of the surface and the fluorescence detectors used at the Pierre Auger Observatory.

## I. GENERAL OVERVIEW

The Cosmic Particle Rain is a 3D application which offers an insight over the nature of cosmic rays, how an extensive air shower induced by a cosmic ray develops in the Earth's atmosphere and how the detection of such events is realised by two complementary detection techniques used at the Pierre Auger Observatory, surface detectors (SD) and fluorescence detectors (FD).

Our application is created in Unity [3], a powerful 2D/3D real time development platform. Unity is mainly focused on game development but is a great tool in various other domains like manufacturing, architecture, engineering and construction where the Augmented and Virtual Reality are extensively used in product development and marketing but also for Movies, Cinematics and 3D Animations creation. Overall Unity is a widely used platform which offers great user support and documentation [4] and it enables users to develop applications on a variety of operating systems (Windows, Linux, Mac OS, Android, iOS) but also directly on websites through WebGL (Web Graphics Library).

The Cosmic Particle Rain is available on Windows. More information about the application installation and run is given in the next section.

## II. INSTALLATION GUIDE AND SYSTEM REQUIREMENTS

The application can be found at the address: <http://www.spacescience.ro/collaborations/auger>, in the "Tools" section of the menu bar, from where anyone could download, upon request, the archive which contains all the files of the static built-in application. There is no need for an installation step, just decompress the archive and launch the application by double clicking **The Cosmic Particle**

**Rain.exe** file. After the execution, the user shall select the resolution and the graphic's quality of the application and then press "Play". For a better experience we recommend to keep the graphics at "Very High" or "Ultra" settings.

In order to run the application offline on a local computer one needs Windows (tests were done on Windows 10) with the graphics driver updated to the latest version. Our tests were made on a PC with Intel I7 4702MQ CPU and Nvidia GTX 760m GPU. Running the application on this configuration we achieved a smooth experience at constant 60 frames per second. However, the application is fully functional and available online in the browser, ready for play, with access from the site mentioned before.

## III. APPLICATION MENU

The application is structured on five sections:

- **Space View:** Here the user can observe a 3D model of the Earth which is hit isotropically by particles of different colors corresponding to a different primary mass of cosmic rays. Upon collision there are developed showers of particles in the Earth's atmosphere. On closer look the user can observe that the majority of cosmic rays are protons followed next by Iron nuclei which dominates the mass spectrum of the ultra high energy cosmic rays.
- **Detection Area:** Here is represented a simplified layout of the Pierre Auger Observatory detection array [1]. With dots are depicted the Cherenkov water tanks, which form the surface detector (SD) of the observatory. The half dodecagons (a twelve-sided polygon) represents the fluorescence detectors (FD) (six of them at four sites: Loma Amarillia, Los Leones, Los Morados and Coihueco). The user can find these locations on the map by hovering the mouse over each site.
- **Surface detector:** In this section the user can observe an emulation of a developing EAS for two different primary particles (Proton and Iron), at three energies ( $10^{17}$  eV,  $10^{18}$  eV and  $10^{19}$  eV) and various incoming shower directions. The arrival direction of the cosmic ray can be defined by the zenith and azimuth angles. The zenith angles gives the inclination of the EAS:
  - 0 degree describes a vertical propagating shower
  - 90 degree describes an horizontal propagating shower parallel with the Earth's surface

The azimuth angle gives the direction of the shower relative to the geographic coordinates (using

the coordinate convention for the Pierre Auger Observatory):

- 0° shower propagating from East
- 90° shower propagating from North
- 180° shower propagating from West
- 270° shower propagating from South

To initialize a shower the user must first select an energy, otherwise only the primary particle will be produced and after the interaction in the atmosphere there will be no secondary particles generated. After the energy is selected, one must choose the values of the zenith and azimuth angles according to the desired arrival direction for the primary cosmic ray. The last step is to press *Proton* if you want to play a Proton induced EAS or *Iron*. To reset the scene press *Reset*.

In this section the shower core (the point where the shower axis intersects the ground) is always placed in the same point (0, 0, 0) given in cartesian coordinates (x, y, z). When the EAS approaches the surface, an ellipse is drawn over the area estimated to be covered by the shower on ground. The actual number and the maximum number of particles developed in the shower are given in the bottom bar section. When particles from the EAS structure collide with the water Cherenkov tanks (the white cylinders), they are highlighted by changing their color in red and increasing their size by 50 %. The number of tanks activated by a shower is shown in the bottom bar. In the top left section can be found additional information about the color legend of the elementary particles developed in the shower and some basic properties like their rest mass and life time.

The viewing angle over a developing shower can be changed between three positions from the keys "F1", "F2" and "F3".

- **Hybrid detector:** In the hybrid section, additional to the SD detector we added a model of an FD building. This building is a simplified 3D model of an FD site from the Pierre Auger Observatory. Similarly to the real FD detectors [5], the 3D model has in it's structure six individual telescopes which are sensitive to the UV rays emitted by an EAS. The activation of each telescope is registered when UV rays passes through their corresponding apertures. If a telescope is activate the color of the aperture is changed corresponding to the color of the primary particle. Also the number of telescopes activated during a developing showers is given in the bottom bar section. More information about the the shower generation and UV rays emission is presented in the next section.

The shower control and the elementary particle's color code is identical to the **Surface detector** section. Also the SD activation algorithm is the same. The main differences are the UV emission which is triggered by the generation of electrons and positrons in the EAS development, the hybrid detection method combining the SD and FD detectors and the mobility of the core

position which can be placed by the user anywhere on the array.

Additional to the three viewing positions over the shower mentioned in the **Surface detector** section, here the user can select two more viewing positions near the FD building by pressing "F4" or "F5" keys.

- **Credits:** A page was created where are mentioned the authors name and its affiliation, acknowledgements and references.

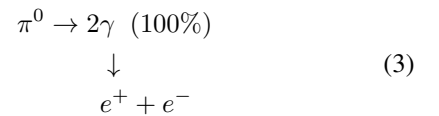
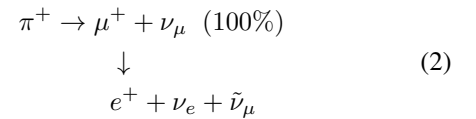
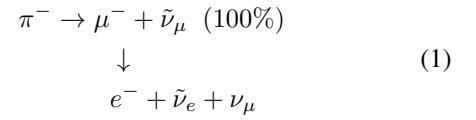
#### IV. EXTENSIVE AIR SHOWER - PHYSICS AND UNITY

The main sections of the application are the **Surface** and **Hybrid Detector**. About these two scenes we will further present details on the extensive air shower development, UV emission, detectors distribution, units used in Unity and scale compared with the real life events.

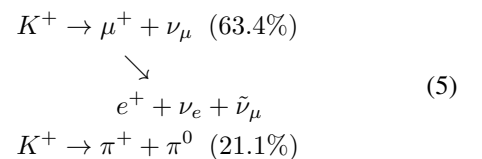
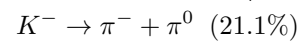
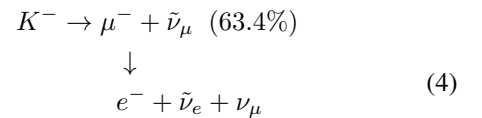
##### A. EAS development

The development of extensive air showers in our application is computed through an algorithm which receives as input the number of particles generated in the primary cosmic ray's first interaction, the mass of the primary and its arrival direction. The algorithm is following some well known interactions and decaying processes which occur in the EAS development. In the first interaction are generated a number of pions, kaons, eta, baryons and nuclei fragments. Each of these particles have a probability of interaction or decay, as function of their life time and interaction path length in air [6]. In our approach we only use the following processes:

- **Pions**



- **Kaons**



$$\begin{aligned} K^{0S} &\rightarrow \pi^+ + \pi^- \quad (68.6\%) \\ K^{0S} &\rightarrow 2\pi^0 \quad (31.1\%) \end{aligned} \quad (6)$$

$$\begin{aligned} K^{0L} &\rightarrow \pi^{+/-} + e^{+/-} + \nu_e \quad (38.8\%) \\ K^{0L} &\rightarrow \pi^{+/-} + \mu^{+/-} + \nu_\mu \quad (32.4\%) \\ K^{0L} &\rightarrow 3\pi^0 \quad (21.6\%) \end{aligned} \quad (7)$$

- Eta

$$\begin{aligned} \eta &\rightarrow 2\gamma \quad (39.13\%) \\ \eta &\rightarrow 3\pi^0 \quad (32.09\%) \\ \eta &\rightarrow \pi^0 + \pi^+ + \pi^- \quad (23.84\%) \end{aligned} \quad (8)$$

In the equations (1-8) the percentage factors are expressing the probability of disintegration of the particle.

The particle generation in the EAS structure is accomplished by using Unity Particle Systems game objects. For each type of particle in each decay process, Particle Systems are instantiated in a hierarchy structure based on the particle decay processes described by equations (1-8). For example, when the life time of  $\pi^0$  meson particles generated in the primary interaction is reached, the daughter Particle System, which will generate  $\gamma$  fotons, is triggered to emit a number of particles proportional to the number of particles emitted by the parent, I.e. the number of  $\pi^0$  generated in the first interaction. Before the emission, we set up each Particle System accordingly to the properties of the particle they will emit: their mass, life-time and type (identified by color). The particle mass is used to approximate the lateral spread of the emitted particles. In Unity a Particle System can be set to emit inside a sphere, cone, doughnut, etc. In our case the Particle Systems are set to emit short bursts of particles inside a cone. The opening angle ( $\Phi$ ) of the cone is variable with the mass of the particle which will be generated, the energy and the mass of the primary cosmic ray:

$$\Phi = 18.0^\circ - \alpha - \beta - \frac{m_p [MeV]}{100} \quad (9)$$

where  $\alpha = 0$  for Iron and 3 for Proton,  $\beta = 0$  for  $E_p = 10^{19}$  eV, 1.5 for  $E_p = 10^{18}$  eV and 3 for  $E_p = 10^{17}$  eV,  $m_p$  is the mass of the particle which will be generated. One can notice that  $\alpha$  and  $\beta$  are suppressing factors of the EAS lateral particle distribution given by the primary mass, respective the energy. Using this formula the lateral distribution of the particles inside an EAS grows with the primary mass and energy, and thus the heavier particles will be concentrated near the shower axis while the lighter particles like the positrons and electrons will have larger lateral spread.

The life time of secondary generated particles can also be modified before the emission. Considering that a primary cosmic ray interacts at  $L = 15$  km above ground and particles are relativistic, traveling with velocities close to the speed of light ( $c = 3 \times 10^8$  m/s), the total development time of an EAS will be:

$$t_{EAS} = \frac{L}{c} = \frac{15 \times 10^3 m}{3 \times 10^8 m/s} = 5 \times 10^{-5} s = 50 \mu s \quad (10)$$

One can notice that eq. (10) is only an estimation for the showers time development. In a rigorous calculation one should take into account the time and space relativistic effects, as well as the curvature of the shower front. The secondary particles developed by the showers have different arrival times at the ground level in correlation with the geometry of the shower. This is an important property of the EAS's used by surface detectors and radio arrays to reconstruct the geometry of the showers and implicitly the arrival direction of the primary cosmic ray.

In our application an EAS has a total development time of  $t_{Unity} = 30$  seconds for vertical showers and  $t_{Unity} = 35$  seconds for inclined showers. In conclusion the EAS development speed is slowed down by a factor of:

$$f = \frac{t_{Unity}}{t_{EAS}} \approx \frac{35 s}{5 \times 10^{-5} s} = 7 \times 10^5 \quad (11)$$

compared to the real events. As the shower is developing in our application much slower compared to the real life events the particle life times have been transformed as shown in table 1.

Particles Life Times [s]	Unity Life Times [s]
$10^{-19} - 10^{-11}$	0 - 1
$10^{-11} - 10^{-7}$	1 - 3
$> 10^{-7}$	$> 3$

TABLE 1: Time conversions for particle life times used in our application

The inclined EAS's have to traverse longer distances before they reach the ground compared to the vertical showers. Also the particles which are generated in the early development stages of the inclined showers are traveling long distances in the upper layers of the atmosphere where the air density is much smaller, decreasing thus interaction probability of the particles. To emulate this property of the showers in our application we increased the particle's life time in Unity with the zenith angle of the shower:

$$\tau = \tau + \tau \cdot \frac{\theta[^\circ]}{1000} \quad (12)$$

By using a surface detector scientists can reconstruct the EAS's core position and geometry through time correlation analysis of the signals measured by each station. The inclined showers generate a larger footprint over the detection area along the arrival direction of the primary cosmic ray. This process can be viewed with the implemented surface detector in our application by changing the azimuth and zenith angles of the generated showers.

Another property of the inclined showers is reflected by the muonic component. Since the mesons generated in the upper layers of the atmosphere have a smaller interaction probability they usually decay in muons which are very penetrating particles. Because particles in the inclined showers travel long distances before they reach the ground, the electromagnetic component (electrons, positrons and photons) is strongly suppressed. As a result the vast majority of particles from inclined events observed at the ground level

are muons [7]–[9]. This EAS property is emulated in our application too. Vertical showers are developing on smaller distances compared to the inclined ones and more particles from both electromagnetic and muonic components reach the ground's surface. With the increase of the zenith angle the number of electrons and positrons at the ground level falls abruptly, while the muonic component even if it is diminished, can still be observed.

The development of the shower also depends on the primary particle mass and energy [7]. Heavier cosmic rays interact earlier in the atmosphere and as consequence the induced showers develop faster and reach their maximum in size at a higher altitude. At the same primary energy heavier cosmic rays generate showers with a larger number of particles which cover a greater area at the ground level. This behaviour can be seen in the shower generation and its development implemented in the application. Compared to Proton, the Iron cosmic ray interacts with 0.5 s sooner in the atmosphere, the shower generated by it develops with 20 - 25 % more particles and the lateral particle distribution is with 10 - 30 % larger.

### B. Fluorescence emission

When the electrically charged particles from extensive air showers propagate in the Earth's atmosphere they interact on their path mainly by ionization and excitation of air molecules. The majority of charged particles are generated in the electromagnetic component of the shower, i.e. electrons and positrons. Because the air has 78% nitrogen in its composition, the energy loss of the charged particles in the processes of the molecular nitrogen ( $N_2$ ) excitation is fairly dominant, which is rapidly followed by fluorescence emission [5]. The nitrogen fluorescence light is emitted in the bandwidth of 300 - 440 nm, which correspond to the UV light spectrum, invisible to the human eye.

In the EAS detection the fluorescence light of the shower is observed using special telescopes sensitive to UV light. Using the fluorescence light scientists can reconstruct the longitudinal development of the shower and determine the energy, mass and arrival direction of the primary cosmic ray.

In the present application we have described the fluorescence emission of the EAS's using UV rays which are propagating from the shower axis towards the lateral side of the FD detector. The telescopes activation is triggered when rays pass through their apertures. To generate the rays we used the same Particle Systems as were used in generating air showers. With five Particle Systems we formed a game object which we will refer to as a *ray generator*. During the EAS propagation, the ray generator is placed on the shower axis, directed towards the fluorescence detector and all five Particles Systems are set to emit. The rays of UV light are rendered as trails of the emitted particles. Once the trails collide with the FD building they disappear and the ray generator is repositioned on the shower axis. At each new frame - 60 times per second - the application reads the position of each particle generated in the shower. To place the ray generator exactly on the shower axis the algorithm

searches the nearest particle to the EAS axis and assigns that position to the ray generator. After the repositioning, the application finds the distance between the ray generator and FD building and evaluates the speed of the emitted UV rays to reach the FD building in one second. The UV ray emission process is conditioned by the presence of the electrons and positrons in the EAS structure.

### C. Scene scaling

Through this application we want to offer an overview on the EAS generation and the detectors response, all in one frame. To achieve this target the implementation of a one to one scale between the real life events and the recreated scene was not possible. The objects scaling in the application was optimized to give an easy understanding over the EAS generation and detection, and so, the user must keep in mind that real events develop much faster and cover much larger distances.

## V. ACKNOWLEDGEMENTS

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## VI. CREDITS

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Terms of use: This application is publicly free for use on educational and outreach purposes only. Its source and author's credits are mandatory to be mentioned while using it. It could either be accessed directly in the browser here: <http://www.spacescience.ro/collaborations/auger/>, or downloaded upon request.

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