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3D VISUALIZATION FOR SIMULATED EXTENSIVE AIR SHOWERS (EAS) USING CORSIKA AND BLENDER 3D

G. CHIRIȚOI[1], A. JIPA[2], E. M. POPESCU[1]

[1]Institute of Space Science, Atomiștilor 409, RO-077125, Bucharest-Măgurele, Romania
E-mails: gabriel.chiritoi@spacescience.ro; empopescu@spacescience.ro
[2] Atomic and Nuclear Physics Department, Faculty of Physics, University of Bucharest,
P.O. Box MG-11, RO-077125 Bucharest-Magurele, Romania, E-mail: jipa@brahms.fizica.unibuc.ro

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Abstract. In order to understand the possible sources of Ultra-High Energy Cosmic Rays (UHECR), due to the low flux, large ground based experiments have been developed for observing the Extensive Air Showers (EAS) produced by the interaction of the primary particle with the Earth atmosphere. Air shower simulations are a vital part of the design of air shower experiments and the analysis of their data. Moreover, visualization offers a very powerful tool for the analysis and understanding of scientific data especially when one is presented with complex situations. The objective of this paper is to present a highly interdisciplinary approach for the realistic visualization of EASs that combines physics phenomenology and advanced 3D animation.

Key words: ultra-high energy cosmic rays, extensive air showers, Corsika, Blender 3D, data analysis, 3D visualization.

1. INTRODUCTION

Cosmic rays (CR) are energetic particles of extraterrestrial origin that enter the Earth's atmosphere from outer space. They consist of several types of particles, both charged and neutral, from protons, atomic nuclei, electrons, antiprotons, positrons, and photons to neutrinos. Ultra-High Energy Cosmic Rays (UHECR) are CR with energies in excess of $\sim 10^{19}$ eV that hit the Earth at a very low flux [1]. The flux that can reach values of less than one particle km^{-2} sr^{-1} century^{-1} for energies above $\sim 10^{20}$ eV, and therefore UHECR can only be detected through the effects of their interaction with the Earth's atmosphere, *i.e.* through the Extensive Air Showers (EASs) they produce when colliding with molecules in the atmosphere.

The origin of UHECR, the mechanisms that accelerate them to such ultrahigh energies as well as their exact composition are still open issues in astrophysics, and all approaches to solving them are based on accurate measurements of the type, energy and arrival direction of the primary particles initiating the EAS. Under these circumstances, EAS simulations are a vital part of modern UHECR experiments such as the Pierre Auger Observatory, JEM-EUSO, TUS, Antares, Km3NeT, IceCube, CTA, TAIGA, etc., as they are used not only in their design, but also for the development of dedicated shower reconstruction methods and algorithms for the identification of the properties of the primary particles.

2. AIR SHOWERS

As mentioned above, and as illustrated in Fig. 1, UHECR are very rare events that can only be detected through their interaction with the Earth atmosphere by very large volume detectors.

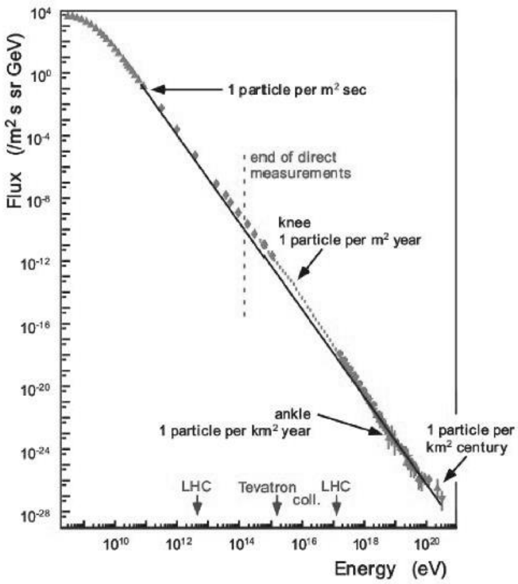

Fig. 1 – The energy spectrum of cosmic rays.

The development of the shower in the atmosphere depends on the type of primary particle, *i.e.* on whether it is a photon or a hadron. In the particular case of hadronic showers, the shower development depends on the hadronic and electromagnetic interactions of the shower particles with the air, their interaction cross sections, the secondary particle production, decays of unstable particles and the transport through the atmosphere, including energy loss, deflection, etc. as illustrated in Fig. 2. The initial hadronic reaction produce pions ($\pi^{\pm}$, π^{0}) which in turn decay into muons ($\mu^{\pm}$) and gammas (γ), thus giving rise to the electromagnetic and muonic components of the shower.

For air showers with energies exceeding ~10^{15} eV, the shower maximum penetrates to half the vertical atmospheric depth or more. The number of particles in the cascade is large enough for the remnant of the shower to be detected by an array of individual particle detectors on the ground such as scintillator counters or water Cherenkov detectors (WD). As the extensive air shower develops in the Earth's atmosphere the relativistic charged particles travel actually faster than the speed of light in the air. As a result, they emit Cerenkov light which can be detected at the ground with air Cerenkov telescopes. However, ground based sampling detectors only see a small part of the shower. For precise energy measurement it is desirable to observe the full shower development. This can be achieved by using fluorescence telescopes which detect the near-UV radiation emitted by the nitrogen molecules excited by collisions with the shower's secondaries.

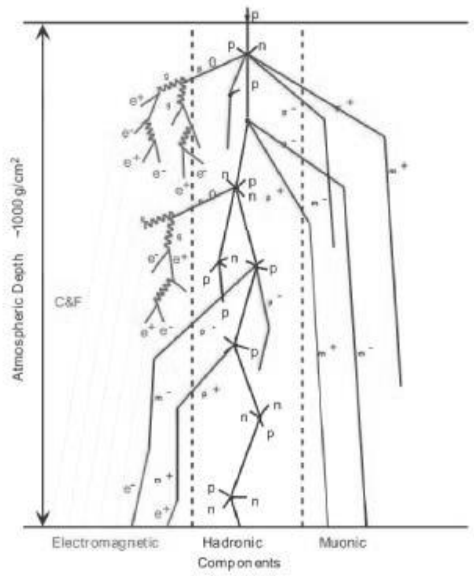

Fig. 2 – The schematic development of hadronic EAS.

3. EAS MODELING AND THE CORSIKA SOFTWARE PACKAGE

Building a realistic air shower model requires several important ingredients, such as the type, energy and direction of incidence of the primary particle, the composition and layering of the interaction medium (the atmosphere) and the interaction channels (primaries and secondaries can be virtually any known particles being produced in collisions such as nuclei, p, n, $e^{\pm}$, γ, $\mu^{\pm}$, $\pi^{\pm}$, π^{0}, $K^{\pm}$, ρ, Ω, Δ, Λ, Σ,...) with their associated probabilities and specific crosssections. Tracking, deflection in the Earth's magnetic field, multiple scattering, energy loss, absorption, ionization, fluorescence and Cherenkov light production must also be taken into account.

When moving on from shower modeling to shower simulations, all of the above need to be put together into a unifying framework that will ultimately provide a clear and consistent picture of the entire air shower. Most such frameworks use the well-known Monte Carlo technique, which is the ideal tool for integrating all the elementary ingredients mentioned above into a complex and consistent numerical model of the whole shower.

An example of such an air shower Monte Carlo simulation framework is CORSIKA (Cosmic Ray Simulations for Kascade) [2]. CORSIKA is a program for the simulation of extensive air showers initiated by high energy cosmic ray particles to a high degree of detail, and which uses, whenever possible, proven and/or validated components and algorithms. For high energy hadronic interactions it uses dedicated packages such as QGSJET, DPMJET, and EPOS (models which are based on the successful Gribov-Regge theory of multiple Pomeron exchange), SIBYLL (a minijet model with Gribov-Regge type of features), while FLUKA and UrQMD are used for hadronic interactions at low energies.

4. THE SIMULATION OF THE EAS

Referring now to the practical aspects of simulating air showers with the CORSIKA package [3], the amount of computing time and disk space needed for such a simulation grow approximately linearly with the energy of the primary particle. As a 10^{15} eV shower needs about one hour to run and produces and output of close to 300 MB, it is straightforward to estimate that a single shower at 10^{20} eV and with a total number of about 10^{11} secondary particles, needs about 10^{5} hours (= 11.4 years) to complete and a storage space of ~30 TB. This is obviously impractical.

Therefore, statistical subsampling (or thinning) [4] is used to discard most of the shower particles and follow only a representative subset of them with appropriate weights to account for the discarded ones. Thinning sets in once the particle energies drop below a certain threshold (typically 10^{-6} of the primary particle energy) allowing for a complete (*i.e*. no thinning) development of the initial segment of the shower. While the energy and the average properties of the shower are preserved, thinning enhances statistical fluctuations and may bias the simulations in regions where only few particles are followed, *e.g.* at very large core distances.

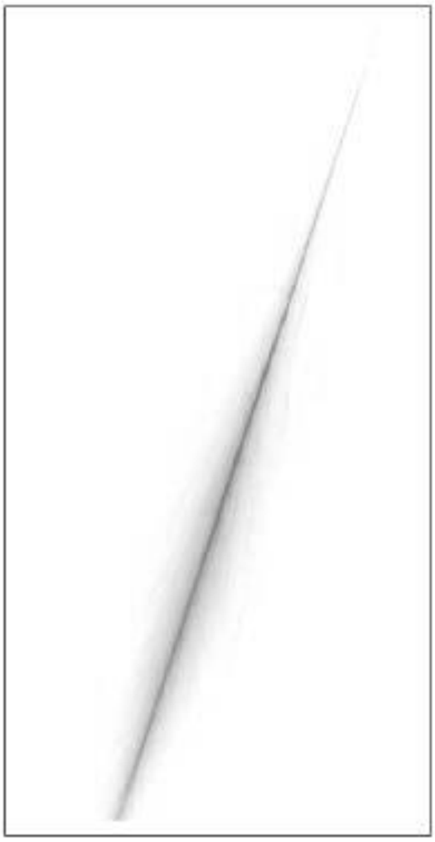

Fig. 3 – Proton, 10 TeV, $\theta = 20°$; *x-z* projection.

In order to visualize the output [5], CORSIKA uses the PLOTSH and PLOTSH2 graphing modules to generate plots of the air shower. However, these plots offer only 2D plotting options with minimal amount of user control, as illustrated in Fig. 3.

5. BLENDER 3D VISUALIZATION

The CORSIKA output data necessary for the visualization of the air shower is contained in the .track binary files, which contain the entire information about the shower particles. In particular, they contain information about the particle kind, energy and occurrence, *i.e.* the time and position (*ts*, *xs*, *ys*, *zs*) in the 3D space of the beginning of the particle trace and the time and position (*te*, *xe*, *ye*, *ze*) of the end of the particle trace. In order to use this data for visualization, a Perl script was developed to convert the .track output files of CORSIKA into a text file format appropriate for the input into the BLENDER software [6].

BLENDER is a software package aimed at supporting high-resolution, production quality 3D graphics, modeling, and animation. It is public open-source software available for several 32-bit and 64-bit platforms several operating systems under the GNU Public License. The graphical user interface (GUI) is designed and streamlined around an animator's production workflow with a Python application program interface (API) for scripting. The final composited output can be high-resolution still frames or video.

It should be emphasized that while the BLENDER package has several applications in game theory and design, as well as for data visualization in biology, fluid mechanics and astronomy, this is the first application of its kind to be used for the visualization particle physics and astrophysics data.

The BLENDER core is written in C, with C++ for windowing and Python for the API and scripting functionality. Native Blender files (*.blend) contain headers with identifiers, pointer sizes, endianness, and versioning. These headers are followed by data blocks with sub headers containing identifier codes, data sizes, memory address pointers, and data structure indices. Each block contains data arrays for object names and types (mesh, light, camera, curve, etc.), data types, data lengths, and structures, which may contain sub arrays of the fields. The data block for an animated scene consists of structures detailing objects and their properties – locations of vertices, edges, faces, and textures, and how those might be affected by a given keyframe. A sample of how these data structures fit together in the workflow paradigm is shown in Fig. 4.

In order to obtain a 3D visualization of EAS simulated in CORSIKA, a Python script was developed to import the text files converted from the binary .track file. The script reads the information in each file, and generates for each particle trace a NURBS Curve. The NURBS Curve object is characterized by two handles, which define the position in 3D space where it will be generated as well as the shape of the curve. The (*xs*, *ys*, *zs*) and (*xe*, *ye*, *ze*) data will be used as coordinates for the handles. The ts and te data will be used as keyframe for the animation. As the code reads line-by-line the text file, the number of lines (events) defines the time for curve generation, and the more events, the longer it takes to generate a line.

The main issue of visualizing the output in CORSIKA arises from the latter's inability to handle the data time sequencing, as well as from the lack of a 3D rendering framework. This issue is trivially solved in BLENDER, which allows for the real-time development of the shower in the 3D space, as illustrated in Fig. 5, for user-control of the viewing parameters as well as for user-controlled selection of specific time slices in order to analyze the EAS development at specific stages [7].

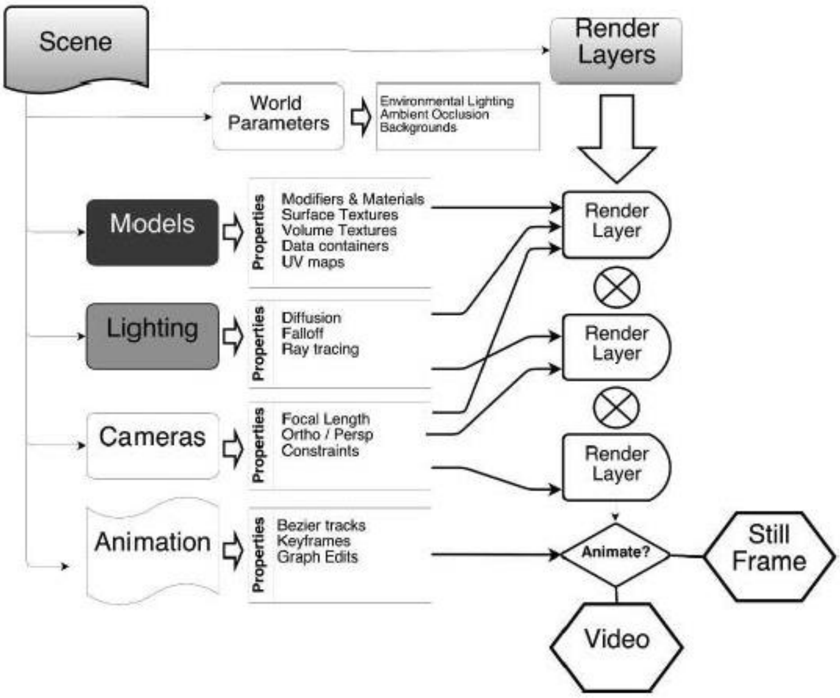

Fig. 4 – Data object structures and the flow in Blender. Model, lighting, camera and animation properties are fed into different render layers. These render layers are then composited into a final video or still frame.

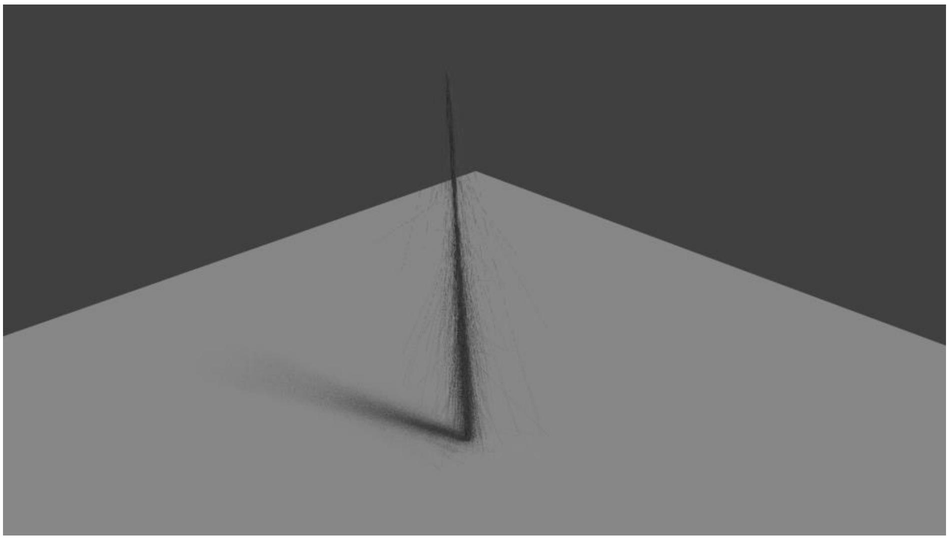

Fig. 5 – Still frame rendering of a proton generated EAS, 40 TeV, $\theta = 10°$.

REFERENCES

1. Johnannes Bluemer, Ralph Engel, and Joerg R. Hoerabel, *Cosmic Rays from the Knee to the Highest Energies*, arXiv:0904.0725.v1(2009).
2. CORSIKA, http://www-ik.fzk.de/corsika/.
3. Marco Alania *et al*., *Air Shower Simulation*, Third School on Cosmic Rays and Astrophysics, August–September 2008, Arequipa, Peru.
4. M, Kobal, Astropart. Phys. **15**, 259 (2001).
5. Jan Malinowski, Anna Smialkowska, *Visualization of the extensive air shower and the estimation of its parameters*, Annales UMCS Informatica **AI X**, 1 87–92 (2010).
6. BLENDER 3D(http://www.blender.org/).
7. Several 3D animations and stills of EAS rendered in BLENDER are available at http://www2. spacescience.ro/heat/eas_animation.html.