UNIVERSIDADE DE SÃO PAULO INSTITUTO DE FÍSICA DE SÃO CARLOS

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Detection prospect of Cherenkov radiation from cosmic rays using a fluorescence detector

São Carlos

2020

Detection prospect of Cherenkov radiation from cosmic rays using a fluorescence detector

Dissertation presented to the Graduate Program in Physics at the Instituto de Física de São Carlos, Universidade de São Paulo, to obtain the degree of Master of Science.

Concentration area: Basic Physics

Advisor: Prof. Dr. Luiz Vitor de Souza Filho

Corrected version (Original version available on the Program Unit)

> São Carlos 2020

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> Martins, Edyvânia Emily Pereira Detection prospect of Cherenkov radiation from cosmic rays using a fluorescence detector / Edyvânia Emily Pereira Martins; advisor Luiz Vitor de Souza Filho corrected version -- São Carlos 2020. 85 p.

Dissertation (Master's degree - Graduate Program in Basic Physics) -- Instituto de Física de São Carlos, Universidade de São Paulo - Brasil , 2020.

1. Direct Cherenkov. 2. Monte Carlo simulation. 3. Cosmic rays composition. I. de Souza Filho, Luiz Vitor, advisor. II. Title.

ACKNOWLEDGEMENTS

I am profoundly thankful for my family, who over the years has given me support and encouragement, always present regardless of distance. Particularly to my parents, Marivone and Edmilson Martins, for the countless sacrifices made to provide me with the best education possible; and to my sisters, Emanuelly and Elayne Martins, who have shown me the power of transformation and resilience.

To my advisor, Vitor de Souza, who welcomed and encouraged me at each stage of this master's program. Thank you for the challenges and the faith in my ability to overcome them.

To the Astrophysics working group, I am grateful for the guidance, in particular to Guilherme Fiusa, Luan Arbeletche, Aion Viana, Alexandre Benatti, Andrés Delgado, Humberto Martínez, Maria Kherlakian, Moacyr Botelho, Pedro Ivo, and Rodrigo Lang. Our conversations were essential to the progress of this work.

Without support from my dear friends, this would have been a much harder task. I express my gratitude to Mariana Santana for her continued reassurance and unparalleled friendship, to Raul Prado for the much valuable inspiration and companionship and to Larissa Aquino and Adriane Leal for the fun times. I also appreciate Caio Cesar with whom I shared the desire to attend graduate school, Tayse Maia and Klécio Lima for all the uplifting conversations and Caio Antony for the fresh perspective in life.

I acknowledge the National Laboratory for Scientific Computing (LNCC/MCTI, Brazil) for providing HPC resources of the SDumont supercomputer, which have contributed to the research results reported within this work. I also acknowledge the support by FAPESP (Fundação de Amparo à Pesquisa do Estado de São Paulo) under the FAPESP Project 2015/15897-1. This study was financed in part by the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior - Brasil (CAPES) - Finance Code 001.

Last but not least, I am thankful for my *alma mater*, Universidade Federal de Campina Grande, where I had the fortune to be instructed by professors who invited me to discuss various topics and from whom I had full support to pursue this path.

"For the remaining fields of cosmic ray physics, astrophysics and cosmology, questions related to chemical and, if possible, isotopic composition, spectral features, time variation, anisotropy of arrival direction and the origin of the most energetic primary cosmic rays are of prime interest." Peter Grieder

ABSTRACT

MARTINS, E. E. Detection prospect of Cherenkov radiation from cosmic rays using a fluorescence detector. 2020. 85p. Dissertation (Master of Science) - Instituto de Física de São Carlos, Universidade de São Paulo, São Carlos, 2020.

The energy spectrum of cosmic rays is governed by a power law in energy with its spectral index being variable; it is also understood that above 4×10^{19} eV a suppression on the incoming flux is present. The composition can only be directly measured up to about $10^{14} \,\mathrm{eV}$ with satellite and balloon-borne experiments. At greater energies, the study of cosmic rays occurs through the detection of air showers and the inference of the primary particle's (or nucleus') information by comparing the data to shower simulations, which in its turn depends heavily on the chosen hadronic interaction model. The evaluation of Cherenkov light emitted by the passage of an incoming nucleus through the atmosphere reduces the dependence on hadronic interaction models to recover information on the primary. We investigate in this work the detection prospect of such direct Cherenkov photons by the fluorescence telescopes at the Pierre Auger Observatory. Simulations using the Monte Carlo method were developed to forecast the number of photons produced by an iron nucleus, as well as their distribution at ground level, for different energies, incidence angles, and distance of the shower core to the telescope. A simple simulation on the main aspects of the measurement procedure was carried out taking into account the telescope's limited field of view and the signal to noise ratio. The study culminates in the expected number of events to be detected per year at the Auger Observatory, given distinct iron nuclei concentration scenarios on the all-particle flux of cosmic rays.

Keywords: Direct Cherenkov. Monte Carlo simulation. Cosmic rays composition.

RESUMO

MARTINS, E. E. **Possibilidade de detecção de radiação Cherenkov produzida por raios cósmicos utilizando um detector de fluorescência**. 2020. 85p. Dissertation (Master of Science) - Instituto de Física de São Carlos, Universidade de São Paulo, São Carlos, 2020.

O espectro de energia dos raios cósmicos é governado por uma lei de potência na energia cujo índice espectral é variável; sabe-se que a partir de 4×10^{19} eV existe uma supressão no fluxo de partículas. A composição só pode ser medida diretamente até aproximadamente $10^{14}\,\mathrm{eV}$ com experimentos em satélites e balões atmosféricos. Em energias mais altas, o estudo dos raios cósmicos acontece através da detecção de chuveiros atmosféricos e da inferência das informações da partícula (ou núcleo) primária ao comparar os dados à simulações de chuveiros, que por sua vez dependem fortemente do modelo de interação hadrônica adotado. A avaliação da radiação Cherenkov emitida pela passagem de um núcleo atravessando a atmosfera reduz a dependência nos modelos de interação hadrônica ao recuperar informações do primário. Investigamos neste estudo a possibilidade de detecção destes fótons Cherenkov diretos com os telescópios de fluorescência do Observatório Pierre Auger. Foram desenvolvidas simulações usando o método de Monte Carlo para predizer a quantidade de fótons produzida por um núcleo de ferro, bem como a distribuição ao nível do solo, para diferentes energias, ângulos de incidência e distância entre o centro do chuveiro e o telescópio. Uma simulação simples dos principais aspectos do procedimento de medida foi implementada levando em conta a limitação do campo de visão dos telescópios e a razão sinal ruído. O estudo culmina no número esperado de eventos a serem detectados por ano no Observatório Auger, em diferentes cenários de concentração de núcleos de ferro no fluxo total de raios cósmicos.

Palavras-chave: Cherenkov direto. Simulação em Monte Carlo. Composição dos raios cósmicos.

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1 INTRODUCTION

Since 1912 it is known that particles coming from outside our atmosphere are the source of the air ionization measured by Victor Hess (3) and his contemporaries. Before such discovery reported by Hess, it was hypothesized that the source could be radioactive elements at the ground. In order to test this, several balloon-borne measurements were carried pointing towards an increase of the ionization with height, which is incompatible to a source on Earth.

From this point on, the study of the sources, transport and acceleration mechanisms and the interaction of such energetic particles with Earth's atmosphere promoted the development of the astroparticle physics field. It has also allowed insights on correlated areas, such as the discovery of unstable particles, first reported by Lattes *et al.* (4), and discussions on high-energy interactions between particles.

From the theoretical side, the acceleration mechanism models are continuously being improved, in the task to agree with recent experimental data. While from the experimental perspective, we still have challenges to accurately recover information such as cosmic ray's, CR, charge and energy, since for higher energies the low flux over the Earth turns their direct detection impractical.

Aiming to unveil properties of the high-energy CR flux, recent experiments have relied on the detection of Extensive Air Showers, EAS, produced by the passage of those energetic particles through the atmosphere. However, the recovery of information on the incoming (or primary) particle depends highly on the description of hadronic interactions at those energies, which are much higher than those achieved in collision experiments. This means that the interpretation of the data collected by air shower experiments is limited by the reliability of the adopted interaction model.

The Imaging Air Cherenkov Technique, IACT, consisting of telescopes collecting Cherenkov radiation from energetic charged particles, have been deployed to investigate gamma-ray events by pointing towards the sources. Recently, this technique has been used to explore the iron component of CR in the TeV energy region. (5) Inspired by this, we will investigate the possibility of detection, with fluorescence telescopes, of Cherenkov photons produced by primary iron nuclei.

Since the Cherenkov light production preceding a shower is strongly related to the primary's charge (or atomic number, for incoming nuclei), its detection can contribute to a better understanding of the CR composition at energies where the direct detection of those particles is difficult. By using this technique, it is possible to reduce the dependence on hadronic interaction models to recover information on the primary, which has been, so far, a great challenge in the area.

To provide the reader with some background on the cosmic rays topic, we briefly discuss in chapter 2 the sources, acceleration mechanisms, and propagation towards Earth of these energetic particles. We also provide some information on the outcomes of the interaction of a primary particle with the atmosphere, discussing how these secondary particles can contribute to the overall understanding of CR, and focusing on the Cherenkov light production.

The refractive characteristic of a medium is deeply connected to the Cherenkov radiation generation. Since the medium of the CR interaction is the Earth's atmosphere, we discuss in chapter 3 some characteristics and models to describe it. Atmosphere models are widely deployed in simulations of extensive air showers, providing a simplification in an overall complex task.

The study would not be coherent in the absence of a detection scenario, therefore chapter 4 is dedicated to the Pierre Auger Observatory, describing the detection techniques adopted and the information it renders. This chapter allows the reader to further understand the context in which this work is related to.

The methodology of the simulations developed in this work will be described in chapter 5, explaining the necessary simplifications and considerations made. Following, we provide in chapter 6 the expected number of events to be detected at the Auger Observatory, along with comments and interpretation of the results.

Finally, in chapter 7, we provide a summary of the work along with the main results, and indications on what could be further investigated in this theme.

2 COSMIC RAYS AND ITS INTERACTIONS WITH THE ATMOSPHERE

With the continuous efforts of several experiments, we now understand that the flux of cosmic rays is a power law in energy, with its spectral index varying with energy. The index variation is caused by source location and acceleration details, propagation effects and composition evolution. It is also understood that above 4×10^{19} eV a suppression on the incoming flux is present, this being most probably caused by interactions with the background radiation and limitations on the acceleration mechanisms.

On their way from the source the cosmic rays, CR, and gamma rays, GR, are subject to interactions with gas, dust, radiation, and magnetic fields, which implies that the spectra and composition at the source must be different from what is observed at the top of Earth's atmosphere. The acceleration and transport of primary particles, nuclei, and radiation will be briefly discussed in section 2.1.

Upon arrival at Earth's atmosphere, CRs enter a more dense region, which enhances the probability of interactions. The incoming high-energy particle interaction with the air will give rise to a cascading production of several particles - this constitutes an Extensive Air Shower, EAS. In this context, radiation production is also relevant, especially by the fluorescence of atmospheric nitrogen and transient polarization of molecules in the atmosphere. The outcomes of an EAS can be used to probe key aspects of this phenomenon, as will be discussed in section 2.2.

2.1 Fundamentals of Cosmic Rays

2.1.1 Sources of CR and propagation through the interstellar medium

The flux of cosmic rays arriving at Earth forms a broken power law on energy, which comprises values from few GeV^{*} to hundreds of EeV^{\dagger} . The composition and spectrum of cosmic rays will be discussed in greater detail in subsection 2.1.2.

By considering the energy density in cosmic rays, ρ_E , along with our galaxy's radius $R \approx 15 \,\mathrm{kpc}^{\ddagger}$ and disc thickness $D \approx 0.3 \,\mathrm{kpc}$, one can estimate the required power to accelerate cosmic rays in our galaxy's disc. Using an average energy density of $\rho_E = 1 \,\mathrm{eV} \,\mathrm{cm}^{-3}$ the estimated power reads

$$W_{CR} = \frac{\rho_E \pi R^2 D}{\tau} = 3 \times 10^{41} \text{ J yr}^{-1} , \qquad (2.1)$$

^{*} $1 \text{ GeV} = 10^9 \text{ eV} \approx 1.6 \times 10^{-10} \text{ J}$ which is approximately two thousand times the electron's rest energy.

 $^{^{\}dagger}$ 1 EeV = 10¹⁸ eV

[‡] 1 kpc = 1000 pc, parsec. One parsec is an astronomic unit equivalent to 3.086×10^{16} meters.

where the used value for the cosmic ray life-time in the galaxy is $\tau = 3$ million years[§]. We can compare this to an average power output per galaxy from Type II supernova of $W_{SN} = 10^{43} \text{ J yr}^{-1}$ ¶, meaning that this type of event could be enough to account for the cosmic rays' energy. (6) However, other astrophysical objects that can also be considered as CR sources, such as active galactic nuclei, AGN, and neutron stars.

The maximum energy CR can obtain is constrained by the source size and its magnetic field intensity: the nucleus' trajectory must be contained in the astrophysical source for it to be accelerated. This relation was first discussed by Hillas in 1984, presenting what is now known as the *Hillas plot* depicted in Figure 1. Above the red line in the figure, iron nuclei can be confined until achieving energies greater than $E_{max} = 10^{20} \text{ eV}$, while the blue line represents protons achieving maximum energy of $E_{max} = 10^{21} \text{ eV}$.



Figure 1 – Hillas plot resenting the relationship between magnetic field strength and size for several astrophysical objects. The red line represents iron nuclei being accelerated to an energy $E_{max} = 10^{20}$ eV, while the blue line represents protons achieving maximum energy of $E_{max} = 10^{21}$ eV. AGN stands for Active Galactic Nuclei; GRB means Gamma-Ray Bursts; SNR, Super-Novae Remnants; and IGM the Intergalactic medium.

Source: KOTERA; OLINTO. (7)

[§] The mentioned life-time considers the permanence of the particle or nuclei in the galaxy, which can either diffuse out of the disk or interact with the interstellar gas.

This value is obtained by considering the ejection of a shell of material of 2×10^{31} kg with a velocity of 10^7 m s⁻¹ in the supernova explosion. Also taking into account a rate of 2 supernova events per century in a galaxy. In Perkins (6), more details on this approximation can be found.

The process of how the particles gain energy still needs to be fully understood. A well-known acceleration model was first proposed by Fermi in 1949 (8), indicating that the cosmic rays could be accelerated due to collision-less reflections: the ions are reflected by magnetic irregularities in the magnetic field, each time gaining an average energy

$$\left\langle \frac{\Delta E}{E} \right\rangle = \frac{8}{3} \left(\frac{V}{c} \right)^2 \quad , \tag{2.2}$$

being V the velocity with which such irregularities (also called mirrors) are assumed to move randomly. This is known as *second order Fermi mechanism* due to the dependency on V which rules the stochastic energy gain from this process. The conclusion drawn from this theory is that "the spectrum of the cosmic radiation obeys an inverse power law". (8) Nonetheless, this model renders a very slow gain in energy, since the velocities of interstellar clouds in the galaxy are approximately 10^4 times smaller than the speed of light in vacuum c, i.e, $V/c \approx 10^{-4}$.

There is also a *first order Fermi mechanism*, which takes place in the shock front of a Supernova shell expanding against the interstellar medium. A cosmic ray could reflect back and forth from the changing magnetic structures in this front, and since the plasma velocities behind (*upstream*) and in front of (*downstream*) the moving shock are different, the energy gain from the upstream - downstream - upstream motion is

$$\left\langle \frac{\Delta E}{E} \right\rangle \propto \frac{u_s}{c} \quad , \tag{2.3}$$

where u_s is the upstream plasma velocity in the shock rest frame. The resulting differential energy spectrum of relativistic cosmic rays is $\propto E^{-2}$. The slightly steeper measured cosmic ray flux, seen in Figure 3, can be attributed to propagation effects.

Since the Fermi acceleration models, many more have been proposed increasing in complexity the description of the processes related to cosmic rays' energy gain. The most recent ones include the non-linearity which arises from those energetic ions modifying the dynamics in the acceleration environment. A comprehensive review was carried out by Amato and Blasi. (9)

The properties of the interstellar medium remain unknown, therefore a preference between proposed propagation models is not yet feasible. The most simple model is the leaky-box approximation, where the high-energy particles diffuse freely inside a confinement volume, being reflected at the boundaries. At each encounter with the boundary, there is a probability of escape which results in an exponential escape length distribution. The CR's composition imposes constraints on the amount of matter traversed by such particles.

2.1.2 Flux of particles and radiation at Earth

On their way from the source, the CRs and GRs are subject to interactions with gas, dust, radiation, and magnetic fields, which implies that the spectra and composition at the source must be different from what is observed at the top of Earth's atmosphere.

The composition difference can be seen in Figure 2, where a comparison between the GCR - Galactic Cosmic Ray- composition is compared to the solar system's. The differences are a result of interactions of GCR C, N, and O nuclei with the interstellar medium, resulting in lighter elements, Li, Be, B; similarly interactions of Fe produce fragments of Sc, Ti, V. The GCR compositions from Li to Zn are from measurements during solar minimum with the ACE/CRIS \parallel instrument; while the hydrogen and helium compositions are derived from balloon-borne measurements. (10) The solar system abundances are from the compilation by Lodders(11).



Figure 2 – Abundances of galactic cosmic rays and solar system material, normalized to $Si = 10^3$. More details on the data are discussed in the text.

Source: ACE... (10)

ACE - Advanced Composition Explorer: a satellite that collects and analyzes particles of solar, interplanetary, interstellar, and galactic origins.

CRIS - Cosmic Ray Isotope Spectrometer: an instrument on-board of ACE that provides measurements of the isotopes of galactic cosmic ray nuclei from helium to zinc over an energy range of about 100 to 500 MeV/nucleon, by measuring the energy loss of the nuclei as they traverse the equipment.

The all-particle flux as a function of energy can be seen in Figure 3. The flux is scaled by $E^{2.6}$ to a better distinction of the regions where the spectral index changes, named *knee*, *second knee*, and *ankle*. We can also observe a suppression on the flux at $E = 4 \times 10^{19}$ eV. One of the possible explanations for this abrupt decrease is the interaction of ultra-high-energy cosmic rays with the cosmic microwave background, known as the GZK suppression^{**}. Another possibility regard a limitation in energy on the acceleration mechanism.



Figure 3 – All-particle spectrum as a function of energy per nucleus. Flux is multiplied by $E^{2.6}$ for the distinction between the indicated regions with different power law slope. Shown are measurements from several air-shower experiments.

Source: TANABASHI et al.. (14)

^{**} In 1966 Greisen (12) and Zatsepin and Kuzmin (13) proposed that primary protons would interact with the CMB radiation, ultimately producing photons through the decay of pions. The energy threshold for this process is of a few 10¹⁹ eV.

2.2 Interactions with Earth's atmosphere

2.2.1 Extensive Air Showers

As a particle traverses the increasingly dense atmosphere, it is prone to undergo interactions governed by its energy-dependent cross section. The incoming high-energy particle interaction with the air will give rise to an EAS. To describe such interactions, the cascade theory of showers was developed simultaneously by Carlson and Oppenheimer (15) and Bhabha and Heitler (16) in 1936, by describing the successive pair creation (of electrons and positrons) and radiation production, therefore only assessing showers initiated by photons, γ or electrons, e^+/e^- .

The model, now known as *Heitler Model*, HM, considers equipartition of energy during each splitting, which occurs after the parent particle travels one splitting length $d = \lambda_r \ln 2^{\dagger\dagger}$. Therefore, after *n* splittings, there are a total of 2^n particles in the shower. When the charged particles achieve energies where the collision losses are more relevant than radiation losses, the cascading process diminishes abruptly. Even though this is a simplified model, it provides two important information on the electromagnetic component of EAS: the maximum number of e^+ , e^- , and γ is proportional to the energy E_0 of the primary particle, and the depth at which the maximum of particles occurs is proportional to the logarithm of $E_0.(15, 16)$

Inspired by the HM the task to fully describe the EAS proceeded, being noteworthy to discuss Matthews' work. (17) Following Heitler's electromagnetic approach, he developed a hadronic model by considering that such particles interact after one interaction length producing N_{ch} charged pions and $\frac{1}{2}N_{ch}$ neutral pions, which immediately decay into photons developing an EM *sub-cascade*^{‡‡}. The charged pions continue interacting until they reach critical energy where they are all assumed to decay into muons. Analogously to the HM, after n interactions, the total number of charged pions is $N_{\pi} = (N_{ch})^n$. Assuming all charged pions must decay into muons, after the shower development the number of muons is equivalent to the number of charged pions at maximum development $N_{\mu} = N_{\pi}$.

In Figure 4 we can observe the schematics of the models described so far, elucidating the cascading characteristic of EASs. In Matthews' work, it was also discussed the scenario of a *leading particle*: one of the outcomes of an interaction carries a large fraction of the energy, in contrast with the equipartition scenario. This is further discussed in Appendix A.

^{††} In fact, d is the distance over which an electron loses half its energy by radiation; λ_r is the *radiation length*, the mean distance over which an electron loses all but $\frac{1}{e}$ of its energy.

^{‡‡} Each electromagnetic sub-cascade can be described using the Heitler model by considering the parent neutral pion as the primary particle of that model.



Figure 4 – Schematics of Extensive Air Shower components: (a) the electromagnetic and (b) the hadronic cascades. Indicated are the particle initiating each cascade, being a photon on the left scenario, and a proton on the right. The horizontal lines indicate the number of interactions undergone. Although not all produced particles are depicted in the hadronic case, by observing the multiplicity in the n = 1 level it is clear that a greater number of particles is produced. The neutral pions decay into photons which are not shown; each photon generates a new electromagnetic subcascade.

Source: MATTHEWS. (17)

As in the first model, the energy of the primary particle is proportional to the number of particles in the maximum, however in this context both the contributions of muons and electrons are accounted for. Besides that, the muon number contribution was presented to be much stronger in obtaining the primary energy than the electromagnetic counterpart as a consequence of the respective critical energies. This suggested the muon content to be an excellent experimental indicator of shower development and primary energy.

Some techniques have been developed to detect such secondary particles, being the most common the scintillation counters and the water Cherenkov detector, WCD. The first provides a counting of charged particles, while the second relies on the Cherenkov radiation emitted by a medium when a high energy charged particle travels through it. The details of Cherenkov radiation will be discussed in subsection 2.2.3.

The lateral spread of nucleus-initiated showers is much larger than for electromagnetic showers. By employing several WCDs covering a large area, the lateral distribution of secondary particles can be investigated providing the aforementioned experimental indicators. This detection technique is broadly used and will be further discussed regarding the Pierre Auger Observatory in section 4.1.

2.2.2 Fluorescence production

In the previous subsection, we mentioned the importance of the lateral profile of EAS to understand its development and to infer information on the primary particle. The longitudinal profile of a shower is also of great importance, mainly through the already mentioned depth of maximum development.

The access to the number of particles as a function of height is not direct, but by means of its interaction with the atmosphere: either by the excitation of air molecules or by the Cherenkov radiation produced by the passage of energetic charged particles. This subsection focuses on the first.

The fluorescence of nitrogen molecules occurs throughout Earth's atmosphere, since this is a major component it will be discussed in chapter 3. The atmosphere, therefore, becomes a calorimeter as the isotropic fluorescence light is proportional to the energy deposit from developing EASs. The resulting ultraviolet light can be observed from several kilometers in distance from the shower core, which allows for accompanying the longitudinal development of the shower. Another advantage is the possibility of a stereoscopic view of the EAS given the existence of multiple fluorescence telescopes observing the same event.

However, this technique can only be used during clear, moonless nights, which reduces dramatically the duty cycle. The remaining background light from stars and human activity also adds to the total signal detected at the fluorescence telescopes, which can overpower the smaller showers producing less light. The observation conditions in the context of the Pierre Auger Observatory are discussed in section 4.2.

Observing the time structure of the signal at the telescope, the trajectory of the shower can be determined. Only then, it is possible to obtain estimated values on the shower size (number of particles) and depth at the maximum development point, which will be valuable in determining the primary energy.

2.2.3 Cherenkov radiation

The Cherenkov radiation is the consequence of a charged particle moving through a medium with velocities greater than light's velocity in that medium. A moving charged particle provides a local magnetic field, which by its turn stimulates the constituents of that medium to align themselves with such magnetic field, i.e., a transient polarization of the medium. According to Grieder(18), "if the velocity of the charged particle exceeds the phase velocity of light in the medium, the wavelets from all points of the particle track will be in phase with one another under a particular emission angle, θ , measured with respect to the direction of motion". The result is a light cone around the particle's track, depicted in Figure 5.



Figure 5 – Visual representation of Cherenkov radiation cone for an arriving vertically primary. Distinct emission points in the left figure have different emission angles, increasing as the particle approaches the ground level. On the right figure, the XY projection of photons reaching the ground, with the different hues of blue corresponding to the emission height accordingly to the figure on the left. The red line and marker represent the shower core.

Source: By the author

The coherence condition, also known as the *Cherenkov relation*, reads

$$\cos(\theta) = \frac{1}{\beta\eta},\tag{2.4}$$

being $\beta = \frac{v}{c}$, the ratio between charged particle's velocity, v, and that of light in vacuum, c, and η the index of refraction of the medium. This relation can be observed in Figure 6.



Figure 6 – The Cherenkov cone aperture angle θ_c changes through the atmosphere due to the varying refractive index. The graph presents the relation from Equation 2.4 for a primary iron nucleus with energy $E = 10^{18} \text{ eV}$.



Figure 7 – Energy threshold for Cherenkov radiation production for two primaries: proton in blue and iron in red. The values have been calculated for an atmosphere described by the NRLMSISE-00 model for the Pierre Auger Observatory location.

Source: By the author

It is interesting to notice that, for a given index of refraction η , there is a threshold velocity below which no coherent radiation is produced:

$$\beta_{th} = \frac{1}{\eta}.\tag{2.5}$$

Therefore, one can associate a threshold energy for Cherenkov radiation production, which can be visualized in Figure 7 for two primaries, proton and iron, and according to an atmospheric model which will be discussed in chapter 3. As we can infer from the figure, all primary nuclei from H to Fe arriving at Earth with energies greater than $E = 10^{16}$ eV will incite the generation of Cherenkov radiation from 100 km high up to its first interaction point. This is what we address as *Direct Cherenkov*, DC, radiation and is the object of study in this monograph. From this point onward, the secondary particles resulting from the following interactions with the atmosphere, constituting the EAS, will also provoke the emission of Cherenkov radiation, should such particles abide by the energy threshold.

While this kind of radiation can be produced in our atmosphere, the process is also efficient in other media, such as water and ice. In fact, the higher refractive index of water lowers the energy threshold for its production, so secondary particles from the shower can still be detected even if its energy is not enough to induce Cherenkov radiation in the atmosphere. As a comparison, the threshold energy for a muon in water is $E_{th}^{Water} = 0.16 \text{ GeV}$ (considering $\eta = 1.33$), while in air is $E_{th}^{Air} = 4.3 \text{ GeV}$ (considering $\eta = 1.0003$). This will be further discussed in chapter 4 in the context of the Pierre Auger Observatory.

The lateral and longitudinal profiles from extensive air showers translate information from the incoming cosmic ray into other observables, being our task to understand how those relations take place. By exploiting the phenomena described in this section, detection techniques have been developed and are continuously perfected to provide a better understanding of those air-ionizing particles that puzzled Hess and other great scientists.

3 ATMOSPHERE CHARACTERIZATION AND ITS RELATION WITH CHERENKOV EMISSION

The Earth's atmosphere is a large volume of gas surrounding our planet, whose density varies with altitude becoming more sparse as the distance from the surface increases. The main elements are nitrogen and oxygen, with concentrations of 78 and 21% respectively (18) at standard temperature and pressure (STP) conditions; the matter of its content will be discussed in more detail in subsection 3.1.1.

According to homogeneity or temperature, the atmosphere can be divided into layers so that the gas behavior is well predicted in each region as a stationary gas. This concept, however, is not strictly a reliable assumption since the atmosphere is dynamic, presenting seasonal and even daily perturbations. Because the timescales of such perturbations are much larger than those of astroparticle showers, the static assumption shall suffice for this study, and hence the atmosphere's dynamics will not be discussed.

In this chapter, some atmosphere models will be presented and discussed. Those models are convenient when predicting the outcomes of the interactions of cosmic rays with the atmosphere, due to the complexity of the involved processes. From the simple scenario presented in subsection 3.1.2, it is possible to grasp the implications of more detailed description as measurements are incorporated into models, which are described in subsection 3.1.3 and subsection 3.1.4.

Since a vital aspect of this study is the Cherenkov radiation, section 3.3 outlines the connection between its production and the atmosphere characteristics. To finalize, in section 3.4 we evaluate how the latter affects the detection of this radiation by light attenuation.

3.1 Density Profiles

Since the real atmosphere is a complex and dynamic system, it is reasonable to use a simple model in the context of cosmic rays and extensive air shower simulations. In this section we introduce some important aspects of the *standard isothermal exponential atmosphere*l and introduce two other models.

3.1.1 Components of the atmosphere

The atmosphere can be described in two regions according to its composition: the *homosphere* and the *heterosphere*. The first is located at the lower section, from Earth's surface to approximately 88 kilometers high. There, the major constituents of the air are nitrogen (78.08%), oxygen (20.94%), argon (0.934%), and carbon dioxide (0.03%), which

form a uniform mixture of gases and is therefore called the homosphere. (19) Consequently, we can assume a constant mean molecular weight M.

The following region has lower mixing activity and hence does not present a uniform mixture. Conversely, the molecules and atoms tend to arrange themselves in layers according to their masses, thus constituting the heterosphere.

According to Navarra(19), at the lowest level in the heterosphere, the most abundant molecule is dinitrogen (N_2) , from 88 to 200 kilometers above sea level, followed by a layer of mainly atomic oxygen (O) up to 1125 kilometers. From there to 3540 kilometers high is a layer composed mostly of helium atoms (He). Finally, the fourth layer consists of hydrogen atoms (H) stretching up to 9660 kilometers above the Earth's surface, which is the frontier to what is called the *exosphere*. At those altitudes the density is very low, and molecules and atoms can escape from Earth's gravitational attraction.

3.1.2 The Ideal Gas Atmosphere

From the considerations of the last subsection, the atmosphere can be regarded homogeneous with a mean molecular weight M * up to heights around 88 kilometers. In this context, the ideal gas equation Equation 3.1 is valid

$$P = \frac{\rho RT}{M} \quad , \tag{3.1}$$

where P is the pressure, ρ is the density of air, R is the ideal gas constant [†], T is the temperature in kelvin units, and M as described above.

Considering the atmosphere to be in hydrostatic equilibrium, i.e., the outward force due to pressure from the gas is balanced by the inward force due to gravity, the following is true

$$dP = -g\rho \ dZ. \tag{3.2}$$

Here, g is the acceleration due to Earth's gravity and Z the height above sea level.

Combining Equation 3.1 and Equation 3.2, it follows that

$$\frac{dP}{P} = -\frac{gMdZ}{RT}.$$
(3.3)

[†] R = 8.31432 × 10³ [N · m · mol⁻¹ · K⁻¹]

^{*} This value can be approximated to $M = 0.029[Kg \cdot mol^{-1}]$. For the height-dependent values, please refer to 20.
If we assume the *isothermal* simplification, meaning the temperature does not vary with altitude in this homogeneous layer, along with a constant acceleration g, we obtain the solution

$$P(Z) = P_0 \cdot \exp\left(-\frac{gM}{RT} \cdot (Z - Z_0)\right) \quad , \tag{3.4}$$

which turns, with the help of Equation 3.1, to

$$\rho(Z) = \rho_0 \cdot \exp\left(-\frac{gM}{RT} \cdot (Z - Z_0)\right),\tag{3.5}$$

where P_0 is the pressure at ground level Z_0 and $\rho_0 = \frac{MP_0}{RT}$. The fraction $\frac{RT}{gM}$ is referred to as *scale height*. We have derived a simple density profile model considering a homogeneous isothermal atmosphere, which turns out to be exponential in density.

3.1.3 The US Standard Atmosphere

The first US Standard Atmosphere model was published in 1958 based on rocket and satellite data and perfect gas theory. According to NASA, NOAA(20), the temperature and density data derived from such satellite and rocket observations were reviewed in September 1971, revealing the necessity to revise the US Standard Atmosphere from 1962 at altitudes above 50 km. For that, a series of experiments [‡] were conducted throughout June of the following year. As a result, mean temperature-altitude profiles for altitudes between 50 and 90 kilometers were prepared, both annual and monthly.

As we have discussed in subsection 3.1.1, up to approximately 88 kilometers, the mixture is homogeneous. In the heterosphere, two processes are responsible for the separation according to molecular weight: dissociation of molecular oxygen, and diffusive separation. (20) In this region, the effect of vertical winds on the composition is important.

In the construction of the 1976 US Standard Atmosphere, the temperature is expressed as a smooth mathematical function of altitude which establishes a soft transition between the layers. Following is a transcription of the temperature-height profile adopted by this model.

The adopted temperature-height profile between 86 and 1000 km is described as follows:

- a) For 86 to 91 km, the layer is assumed to be isothermal at 186.8673 K.
- b) For 91 to 110 km, a segment of an ellipse is used, assuring a smooth monotonically increasing temperature-height function [...].

[‡] Grenade, pitot-static tube and falling-sphere experiments.

- c) The layer, 110 to 120 km, is represented by a straightline segment in which the change in temperature with altitude, i.e., dT/dZ, is equal to 12 K/km.
- d) The region, 120 to 1000 km, is represented by an exponential function in which T asymptotically approaches 1000 K at heights above 500 km. [...].
- (20, p.29)

It is a common practice to adopt parameterizations on the density profile when the objective is to simulate extensive air showers, dividing the atmosphere into 5 layers and providing for continuity between those strata. A hydrostatic behavior and an exponential dependence of the density on altitude are assumed, yielding:

$$\rho(h) = \frac{b_j}{c_j} \exp\left(\frac{-h}{c_j}\right) \quad , \tag{3.6}$$

where h is the altitude, and b_i and c_j are the parameters for each layer j.

A widely used software for simulating such showers is the detailed Monte Carlo program **CORSIKA (COsmic Ray SImulations for KAscade)**. In its user's guide manual (21), there are 26 parameterizations of atmospheres for few locations and different epochs of the year, which can be incorporated into the simulations, including the 1976 US Standard atmosphere described above. It does not, however, apply to any location on the globe. Conversely, the user has the option to aggregate an additional parameterization for a desired location and epoch. As an example of another atmosphere model that can be applied to any location, the NRLMSISE-00 model is introduced in the next section.

3.1.4 The NRLMSISE-00 Atmosphere Model

The NRLMSISE-00 is an empirical atmosphere model based on its predecessor MSISE-90 model. The philosophy behind the most recent model is that only through continuously adding current data to their databases and subsequently modifying their parameter sets, such empirical models can reflect the present state of the atmosphere. (22)

According to 23, A. E. Hedin and his co-workers combined data from a satellitebased mass spectrometer and ground-based incoherent scatter radars to establish the Mass Spectrometer Incoherent Scatter (MSIS) models: MSIS-77, -83, -86. Above 72.5 km, MSISE-90 is a revised MSIS-86 model taking into account data derived from space shuttle flights and newer incoherent scatter results, being equivalent below that altitude.

The NRLMSISE-00 incorporates a gravity field and an effective Earth radius, which are both latitude-dependent, meaning that the deviation from a spherical shape of the atmosphere is accounted for. Besides that, the model interpolates among newly added and past data sets, some of them covering more than a solar cycle. (22) As stated by Picone et al.(22)

 $[\ldots]$ diffusive equilibrium no longer holds for the MSIS-class models below altitudes of ~300 km. $[\ldots]$ For this reason, the model generation process imposes an approximate hydrostatic equilibrium constraint in the region 80 – 300 km. This couples the lower and upper atmospheric regions, modifying some details of previous MSIS versions.

The data from this empirical model is readily available online [§]. The user must input information such as the date and time as well as geographic location and altitude, obtaining in return data for the concentration of specimens in the atmosphere, e.g. molecular and atomic oxygen and molecular nitrogen, temperature, and total mass density.

In Figure 8 we can see a comparison between the NRLMSISE-00 and the US Standard 1976 models regarding the densities profiles up to heights of 100 kilometers. The NLMSISE-00 values were calculated for a latitude of 35° south and a longitude of 69° west, corresponding to the Pierre Auger Observatory location. The accordance between models is noted up to 40 km which includes the region of the development of extensive air showers; from 40 km upward, the region more relevant for the cosmic and gamma rays interactions with the atmosphere, the differences may become relevant. We have opted for the NRLMSISE-00 model here forward, however, a more detailed comparison of such models regarding the outcomes of simulations was not carried out.



Figure 8 – Density profile for two distinct models, up to heights of 100 km. Depicted in blue is the NRLMSISE-00 model and in red the US Standard 1976.

Source: Adapted from: NATIONAL...;(20) ATMOSPHERIC... (23)

^{\$} https://ccmc.gsfc.nasa.gov/modelweb/models/nrlmsise00.php

3.2 Survival Probabilities

As a primary particle approaches the Earth, it travels through the atmosphere traversing a column depth of matter, X(h), which can be computed as

$$X(h) = \int_{h}^{\infty} \rho(h')dh' \quad . \tag{3.7}$$

The probability P(h) of such particle to survive, i.e., not interact or decay, down to a height h above sea level is

$$P(h) = \exp\left(-\frac{X(h)}{\chi_0}\right) \quad , \tag{3.8}$$

where χ_0 is the interaction length of the particle, which is energy-dependent and describes the usual mass column traveled through by a particle before it interacts ¶. Since the typical energies of cosmic rays are usually much higher than those achieved by accelerators, we rely on high energy interaction models to provide this information. In Figure 9 we can see three interaction models, comparing the energy-dependence of the interaction length for two different primary cosmic rays: proton and iron, respectively.



Figure 9 – Interaction length as a function of the logarithm of energy, for different high energy interaction models.

Source: By the author

In Figure 10 we compare the survival probabilities, for different primary energies, as a primary traverses vertically the atmosphere considering the interaction lengths provided by the Epos LHC model shown in Figure 9. On the left panel, the probabilities for an incoming proton with energies $E = 10^{16}$ eV (green line), $E = 10^{18}$ eV (red) and $E = 10^{20}$ eV (blue) are shown; on the right panel, the probabilities for an incoming iron nucleus with energies $E = 10^{16}$ eV (blue line), $E = 10^{18}$ eV (green) and $E = 10^{20}$ eV (yellow) are shown. As a general trend in both scenarios, the greatest is the primary's energy, the higher occurs the first interaction.

The decay scenario is not considered relevant in this study because the focus will be on the iron nucleus as a cosmic ray, which is understood to be stable.



Figure 10 – Survival probability of a primary cosmic ray traversing an atmosphere described by the NRLMSISE-00 model. On the left, a proton primary, on the right an iron nuclei.

3.3 Refractive Index

The refractive index is a macroscopic consequence of the interaction of radiation with a set of charged particles and their associated fields. The outcome is observed as a delay of the original wave, represented by a change in phase velocity, i.e., the photons appear to move with a velocity $v_{photon} = \frac{c}{\eta}$, being η the refractive index of the medium. The refractive index is dependent on the number density of constituent of the medium, N, being typically greater for dense materials, as is described in the following equation:

$$\eta = 1 + \frac{N \cdot q_e^2}{2\epsilon_0 \cdot m \cdot (\omega_0^2 - \omega^2)} \quad . \tag{3.9}$$

The index of refraction is dependent on the photon's frequency ω as well as on the resonant frequency of an electron bound in an atom from the medium, ω_0 . Here, ϵ_0 is the permittivity of free space, q_e is the electron's charge and m its mass.

According to Bernlöhr(24), " $\eta(\lambda)$ changes by only 5% over the wavelength range 300–600 nm, the range typically covered by photomultipliers"^{||}, therefore in this work the refractive index dependence on the wavelength can be disregarded. This also means that the variations in local density with height will be the cause for a changing refractive index throughout Earth's atmosphere.

The photomultipliers are devices responsible for collecting photons in most detection techniques related to cosmic rays and air showers, such as the ones presented in chapter 4.

3.3.1 Altitude profile

The refractive index can be approximated, as a function of the local density Weast, Astle e Beyer (1986 apud Kümpel(26), 2007), by the following expression

$$\eta(h) = 1 + 0.000283 \frac{\rho(h)}{\rho_0} ,$$
 (3.10)

where $\eta(h)$ is the local index of refraction, $\rho(h)$ is the local atmospheric density, and ρ_0 is the air density at sea level, where $\eta_0 = 1.000283$. Densities are given in $[g \cdot cm^{-3}]$.

From such parameterization, we understand the refractive index behavior through the atmosphere, which will be of vital importance in determining characteristics of the Cherenkov radiation emitted by a CR.

3.3.2 Aspects of Cherenkov Radiation

The phenomenon discovered by Cherenkov in 1934 was qualitatively and quantitatively described by Frank and Tamm (27), providing the energy radiated by a charge moving through a dielectric medium, in the condition that its velocity is greater than the velocity of light in the medium. The total energy radiated by an electron is given by

$$\frac{d^2 E}{dx d\omega} = \frac{e^2}{c^2} \omega \left(1 - \frac{1}{\beta^2 \eta^2(\omega)} \right) \quad , \tag{3.11}$$

where e is the elementary charge, c is the speed of light in vacuum, ω the radiation's angular frequency, and β and η as previously described.

As seen in subsection 2.2.3, there is a dependence of the Cherenkov emission angle with the local refractive index. Therefore it is important to understand how it varies through the atmosphere to accurately estimate this radiation's production.

Apart from the emission angle, the number of Cherenkov photons produced by a charged particle is also dependent on the refractive index. From the Frank and Tamm equation above, it is possible to obtain the number of photons, N_{ph} , radiated along a path of length l within a range of wavelength values; it is given by (18)

$$N_{ph} = 2\pi Z^2 \alpha l \left(\frac{1}{\lambda_1} - \frac{1}{\lambda_2}\right) \cdot \left(1 - \frac{1}{\beta^2 \eta^2}\right) \quad , \tag{3.12}$$

where Z is the charge of the particle, α is the fine-structure constant ^{**}, the wavelengths λ_1 and λ_2 correspond to the extremes of the radiation emission distribution ^{††}, $\beta = \frac{v}{c}$ being v the particle's velocity, and l as described above.

**
$$\alpha = \frac{e^2}{\hbar c} = \frac{1}{137}$$

^{††} The Cherenkov radiation emission spectrum is proportional to λ^{-2} .

3.4 Transmission of photons through the atmosphere

While light traverses the air, it is subject to attenuation and absorption. The former is a consequence of molecular (Rayleigh) and aerosol (Mie) scattering and the latter due to ozone absorption. The light may be scattered into or out of the field of view of the detector, but for the purposes of this work, we consider that the scattered photons are not detectable. Thus, the scattering processes result in a reduction in the number of photons.

The molecular scattering is the most relevant in the context of Cherenkov photons propagation through the atmosphere, as can be seen in Figure 11. Similarly to the survival probability of a particle traversing the atmosphere described in section 3.2, the transmission probability due to Rayleigh scattering, T_R , is dependent on the column of atmosphere traversed (18):

$$T_R = \exp\left[-\left(\frac{|X_1 - X_2|}{X_R}\right) \cdot \left(\frac{400nm}{\lambda}\right)^4\right] \quad , \tag{3.13}$$

where X_1 and X_2 are the slant depth^{‡‡} at emission and detection, respectively (in $g \cdot cm^{-2}$), $X_R = 2974g \cdot cm^{-2}$ is the scaling factor, and λ is the photon's wavelength.

The aerosol scattering tends to affect only 10% to 20% of the photons, as can be seen in Figure 11. According to Grieder(18), the transmission factor due to Mie scattering, T_M , is given by:

$$T_M = \exp\left[e^{\left[-\frac{h_1}{h_M}\right]} - e^{\left[-\frac{h_2}{h_M}\right]}\right] \cdot \frac{h_M}{\sin(\phi)L_M} \quad (3.14)$$

where h_1 and h_2 are the altitudes of emission and detection, respectively (in m), $h_M = 1200$ m is the *scale height*, $L_M = 14000$ m is the mean free path at 360 nm for the Mie scattering and ϕ is the elevation angle seen by the telescope, i.e., the complementary to the zenith angle of the particle's trajectory.

The resulting transmission factor is simply the product of the two previous expressions

$$T = T_R \cdot T_M. \tag{3.15}$$

We can conclude that the transmission factor will vary slightly for each Cherenkov photon produced in the atmosphere.

^{‡‡} Slant depth is equivalent to the atmospheric column density for inclined trajectories. $X_s(h,\theta) = X(h,\theta=0)/\cos(\theta)$, being θ the zenith angle of the trajectory.



Figure 11 – Transmission probability of light traversing the atmosphere from 100 km to 2.2 km high in a vertical path.

Source: BERNLÖHR. (24)

4 THE PIERRE AUGER OBSERVATORY

The Pierre Auger Observatory was designed to study the spectrum of cosmic rays above energies of 10^{18} eV through the detection of secondary particles and radiation produced in the interaction of those CR with the atmosphere.(26, 28) Such energetic primary particles interact with nuclei and molecules in the air, triggering a cascading production of other particles in what is known as *Extensive Air Showers*, EAS, as was described in chapter 2.

Comprising an area of 3000 km^2 , the Auger Observatory was built to be a hybrid facility, with 1660 water-Cherenkov detectors (WCD) triangularly arranged with distances of 1500 m constituting the Surface Detector (SD), and 24 fluorescence telescopes. The telescopes are grouped in 4 Fluorescence Detector sites (FD) overlooking the SD, each with 6 telescopes viewing an aggregate 180° azimuth by 30° elevation field of view. According to 29, there are also additional WCDs forming the *infill* array: covering an area of 23.5 km² and centered 6 km from one of the fluorescence sites, the detectors are placed 750 m apart.

Located in Malargue, Argentina, it is situated 1400 meters above sea level, and since 2004 the Auger Collaboration is reporting data. In the last decade, some enhancements have been introduced, e.g., AERA - Auger Engineering Radio Array (additions in 2010 and 2013) and Auger Prime (29), which is ongoing and comprises several modifications. In Figure 12 we can see the SD, each red dot being a WCD, and the FD with each pair of green lines representing the field of view of the telescopes. In the following sections, the detection techniques will be discussed in the context of the Pierre Auger Observatory.



Figure 12 – Schematics of the Pierre Auger Observatory, Malargue site. Source: THE PIERRE ... (30)

4.1 Surface Detector

According to what was discussed in subsection 2.2.3, when a charged particle travels with velocity v higher than the light's in that medium, Cherenkov radiation is emitted, so exploiting this effect the water-Cherenkov detectors were designed. In the Auger collaboration, cylindrical water reservoirs of 3.6 meters in diameter and 1.2 meters high are filled with 12000ℓ of purified water. Within its structure is a reflective material that allows the detection of the Cherenkov photons by the three photomultipliers located just above the water. The WCD is depicted in Figure 13.

The SD samples the lateral distribution of secondary particles in a shower and can, by comparison on the arrival times in neighboring detectors, give information on the direction of the shower. As discussed in section 2.2, these WCDs can also provide an approximate measure of the primary energy for large showers. The SD has a duty cycle of 100%, detecting events triggered by primary energies above $E = 3 \cdot 10^{18}$ eV.



Figure 13 – Visual representation of a water-Cherenkov detector adopted by the Pierre Auger Observatory.

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Source: THE PIERRE \dots (31)
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4.2 Fluorescence Detectors

The fluorescence telescopes at the Auger Observatory have been designed to detect the isotropic light due to nitrogen fluorescence emitted by extensive air showers, which allows recording the development of the shower through the amount of light detected. It has a circular diaphragm of radius 1.1 m, along with a UV filter glass window. This filter reduces the background light flux, providing an increase in the signal to noise ratio. According to 29, "the light is focused by a spherical mirror of ~ 3400 mm radius of curvature onto a spherical focal surface with a radius of curvature ~ 1700 mm". Each telescope camera is composed of 440 hexagonal photomultiplier tubes, model XP3062 manufactured by Photonis, arranged in 20 columns by 22 rows. Each pixel has a field of view corresponding to an angular aperture of 1.5° . The sampling ratio of each telescope is 10 MHz, corresponding to a collection time of 100 nanoseconds (or 10^{-7} s), and it is sensitive to photons with wavelengths between 300 nm and 420 nm. The fluorescence telescope is depicted in Figure 14.



Figure 14 – Visual representation of a Fluorescence detector station adopted by the Pierre Auger Observatory.

Source: THE PIERRE \dots (31)

Due to the large field of view of 30°, not all light beans arrive with small angles with regard to the telescope's axis, thus provoking spherical aberrations. The usage of corrector lenses diminishes the spreading of light in the telescope apparatus, which otherwise would be significant and would impact negatively on the resolution of the cosmic rays' direction reconstruction. (32) Therefore, in each telescope diaphragm, there is also a ring of corrector lenses with an inner radius of 85 centimeters and an outer radius of 110 centimeters.

The observation of fluorescence light from air showers is only possible on low sky brightness nights, so the sun must be lower than 18° below the horizon, and the illuminated fraction of the moon should be lower than 70% in the middle of the night. The mean length of the observation period is 17 nights each month, rendering a duty cycle of about 15%. Other factors contributing to this low functional time are mainly weather-related, such as strong winds, rain, and snow.

The main objective of the deployment of fluorescence telescopes is to evaluate the longitudinal profile of a shower, gathering information on the shower development and consequently determining the location of the shower maximum, X_{max} . The reconstruction of the FD events allows an estimation of the energy deposited in the atmosphere, i.e., the calorimetric energy E_{cal} of the showers. This estimated energy is not, however, the

total energy of the shower E_{FD} , since some low-interacting particles such as muons and neutrinos carry energy into the ground. (1) This difference is known as the *invisible energy* and can be accounted for, approximately, via WCD since high energy muons deposit energy while traversing the water. Thus, the joint operation of both detection techniques is vital to obtain information on the primary particle's energy more accurately. Besides that, the angular resolution for hybrid events above $10^{18.5}$ eV is better than 0.5° . (29)

4.3 High Elevation Auger Telescopes

The High Elevation Auger Telescope (HEAT) was designed to cover the elevation range from 30° to 58°; its internal structure is very similar to the FD. It is located 180 m in front of the FD site at Coihueco, which can be seen in Figure 12. HEAT constitutes a 5th station, composed of 3 telescopes bays, instead of the usual 6. Another remarkable difference to the usual telescopes is the sampling ratio of 20 MHz, corresponding to a collection time of 50 nanoseconds.

The main objective of this enhancement to the initial design of the Observatory was to reduce the energy threshold of hybrid data. In combination with the SD and the infill array, which is close to the HEAT station, the fluorescence light collected by it allowed the extension on the energy range of hybrid detected showers down to 10^{17} eV. (30) More recently, the Pierre Auger Observatory has evaluated HEAT events^{*} dominated by Cherenkov radiation, allowing to lower the energy threshold to $10^{16.5}$ eV. (1)

4.4 Auger Prime

The Auger Prime project is a collection of enhancements to the Auger Observatory. The main aspect is the installation, over each water tank, of a plastic scintillator (SSD) along with the replacement of the SD electronics. Another significant aspect is the implementation of AMIGA (Auger Muon and Infilled Ground Array), consisting of scintillator detectors buried 2.5 m deep into the ground (~ 20 radiation lengths). This will avoid electrons from being detected in the underground scintillators, resulting in the inference of the muon content responsible for the signal in the nearby WCDs. Therefore, with AMIGA, the collaboration shall have a better estimation of the invisible energy and, thus, on the energy reconstruction.

Regarding fluorescence detection, the Auger Prime project aims to increase the FD duty cycle by operating the telescopes during nights with a higher fraction of the moon being illuminated. This can be achieved by reducing the photomultiplier gain to avoid deterioration of the PTM sensitivity. Tests have been carried out (29), verifying that the PMTs can be operated at low gains and that the measurement of the night sky background is still possible in this scenario using the variance of the measured signal.

^{*} The word *event* denotes here a shower observed by the fluorescence telescopes.

5 THE PROSPECT OF DIRECT CHERENKOV RADIATION DETECTION AT THE AUGER OBSERVATORY

The process described in chapter 2 regarding the production of Cherenkov photons is valid for the passage of cosmic rays through the atmosphere, provided the *primary particle* has total energy greater than the threshold for the production of the coherent radiation. Since the threshold given by Equation 2.5 is also dependent on the refractive index, the main impact of this relationship is on the height where Cherenkov radiation starts being produced by an incoming nucleus.

This radiation preceding an extensive air shower is directly related to two main characteristics of the primary: charge and energy, as indicated by Equation 3.12 providing the number of emitted photons, and by Equation 2.4 defining the emission angle with respect to the primary's trajectory. This means that the detection of direct Cherenkov radiation can contribute to the description of the primary composition. This technique is already being carried out by VERITAS (5), which uses a set of 4 telescopes. The sampling time of those telescopes is a few nanoseconds, allowing for a temporal distinction on the region of emission of said photons. So far, the VERITAS data have contributed to the iron spectrum in the range of 20 TeV to 500 TeV, according to Fleischhack(5).

Considering the importance of obtaining information on the primary, in addition to the Pierre Auger Observatory's ability to detect Cherenkov light with its fluorescence detectors as discussed by THE PIERRE AUGER COLLABORATION(29), we propose here a preliminary investigation of its capability to detect Cherenkov photons from the primary particle using its fluorescence telescopes. In this work, we have run simulations for primary iron with different energies and zenith angles as well as different values of core-to-telescope distances.

In this chapter, we describe the simulation implemented to obtain the expected amount of DC photons to be detected by the fluorescence telescopes at the Pierre Auger Observatory. We have selected a high energy interaction model, EPOS-LCH, to provide the interaction length of the incoming Fe nucleus, and the NRLMSISE-00 model to portray the atmosphere. We consider the primary nucleus' energy to be constant during its propagation.

The entire process was simulated, from production to detection, according to the following sections: Cherenkov photons production (discussed in section 5.1), its propagation and temporal profile (section 5.2), and finally the detection (section 5.3).

We approach this investigation using the Monte Carlo method, which is a numerical technique for calculating probabilities and related quantities by using sequences of random numbers. (33) Using the transformation method, one can reproduce known distributions from its inverse and a set of uniformly distributed random numbers. This is precisely

the procedure used to obtain the height of first interaction of the primary, the azimuthal angle and wavelength of produced photons and the shower core position (for a given core-to-telescope distance).

5.1 Cherenkov light production

Following Equation 3.12, we have computed the number of photons produced every 10 meters of the path traveled by the nucleus, and according to Equation 2.4, the emission angle θ_c is computed, taking into consideration the local refractive index. For each photon, θ_c was drawn following a uniform distribution centered at the computed value and spreading $\pm 5\%$ of this value. The azimuthal angle was also drawn from a uniform distribution, which is responsible for guaranteeing the known conical shape of Cherenkov radiation. Since the Cherenkov radiation spectrum is proportional to $\frac{1}{\lambda^2}$, the wavelength values were selected accordingly via the Monte Carlo technique.

In Figure 15 the total number of photons produced by a primary Fe nucleus is depicted as a function of the slant depth traversed. We can recall that the slant depth of matter was described in Equation 3.7. Since the height of the first interaction varies on an event-to-event basis due to its probabilistic nature, the amount of DC photons also varies.



Figure 15 – Illustrative example of the number of direct Cherenkov photons produced by the passage of a primary iron nucleus as a function of slant depth traversed by the primary. The incidence angle is $\theta = 40^{\circ}$ and the primary energy is $E = 10^{16} \,\text{eV}$.

Aside from its spatial distribution, the attenuation from the scattering processes also impacts the number of detected DC photons, as was discussed in section 3.4. In Figure 16 we observe the number of photons arriving at a telescope located 50 meters away from the shower core as a function of the emission height. As already discussed, the amount of matter traversed by the photons determines the transmission rate through the atmosphere. An iron nucleus with energy $E = 10^{16}$ eV and incidence angle $\theta = 40^{\circ}$ will produce a similar number of photons as indicated in Figure 15, however, only a few dozens will be detected by a telescope, as can be observed in Figure 16. Photons produced higher in the atmosphere will most likely be absorbed, even though the greater emission angles at lower heights also plays a role in the attenuation process. Both Rayleigh and Mie scatterings are henceforth accounted for by the calculation of the total transmission coefficient, given by Equation 3.15.



Figure 16 – Illustrative example of the number of direct Cherenkov photons detected at a telescope 50 meters away from the shower core as a function of the emission height. The incidence angle is $\theta = 40^{\circ}$ and the primary iron energy is $E = 10^{16}$ eV. The different lines indicate the attenuation resulting from the propagation of photons through the atmosphere.

5.2 Time profile

Each Cherenkov photon produced from 100 km high up to the height of the first interaction is propagated through the atmosphere, while also computing an arrival position on the plane of the telescope, a transmission coefficient computed by Equation 3.13, the elevation as seen by the telescope and the arrival time. The velocity of light propagating in a medium, $v_{light} = \frac{c}{\eta}$, was also accounted for by considering the changing refractive index of air.

Therefore, not only the DC photons are scattered away, but they are also slowed down due to the increasingly dense atmosphere as they propagate downwards. As a result, the Cherenkov photons are temporally compressed. According to Grieder (18), in the context of a vertically incident CR, the time delay from a photon produced at 50 kilometers high in the atmosphere with respect to that produced 1 kilometer above ground is of few dozens nanoseconds, varying with the distance from shower-core.

In Figure 17 we can observe the great impact of implementing the effects of refractive index on light propagation. The same number of detected photons, in this event, are more compactly distributed once this effect is accounted for, which ultimately impacts on the detectability of a signal. The time bin size in this figure corresponds to the collection time of HEAT: $\delta t = 50$ ns.



Figure 17 – Illustrative example of the effects of the refractive index on the time profile of the direct Cherenkov photons detected at a telescope 50 meters away from the shower core. The incidence angle is $\theta = 40^{\circ}$ and the primary iron energy is $E = 10^{16}$ eV. On the top panel, values without corrections on light speed, and on the bottom panel, values considering the varying speed of light with the increasing refractive index.

5.3 Detector simulation

The first thing to consider is the limited field of view of the FD from 1.5° to 30° or, for the HEAT telescopes, from 30° to 60° , as detailed in section 4.2 and section 4.3, respectively. As a consequence of these constrains and considering the very small angles of emission for high altitudes discussed in subsection 2.2.3, we must investigate inclined showers in ranges which should complement the elevations of the telescopes: from over 30° to under 88.5° .

Another aspect to consider is the collection time being of 50 ns/100 ns in the scenarios of FD/HEAT. As discussed by Hammond *et al.*(34), the delay on the arrival of photons emitted high in the atmosphere in comparison to those emitted at 1 km is smaller than 100 ns for vertically incident iron nuclei. Even though this delay is expected to increase in inclined showers because of the augmentation on the path traveled by the photons, the sample times from Pierre Auger detectors are still comparable to the expected delay time. The collection time affects both the amount of DC photons and background light to be detected, hence influencing the signal-to-noise ratio (see next subsection).

By considering that the Pierre Auger telescopes have a diaphragm with an aperture of 1.1 m of radius, we computed as detected only those photons which arrive within this distance around the (x, y, z) = (0, 0, 1500)m point, which is the considered location of a telescope.

As discussed in subsection 2.2.3, the emission angle range for DC photons extends up to 0.8°, therefore the elevation angle of those photons, as seen by the telescopes, must be very close to the complementary of the primary's incidence angle. This means that, considering each PMT has an angular aperture of $1.5^{\circ} \times 1.5^{\circ}$, all photons produced by the passage of the primary through the atmosphere will be collected by a single PMT. Besides that, the expected uniform azimuth distribution of incoming CR allows us to consider the field of view of each telescope to be composed of a line of PMTs, for a given incidence angle. That means, for example, that for a shower inclination of $\theta = 40^{\circ}$ all PMTs at elevation corresponding to $\phi = 50^{\circ}$ could observe an event, depending on the core distance to the telescope.

5.3.1 Signal-to-noise ratio

The following step was to evaluate the signal-to-noise ratio, N_{σ} , in each time interval equivalent to the telescope's collection time. We consider a night sky background of 40 photons $[m^{-2} \mu s^{-1} deg^{-2}]$ as suggested by Grieder(18) and which already considers an attenuation in the atmosphere and by the UV filter placed in front of the telescope's diaphragm.

The signal-to-noise ratio is a comparison between the signal in a detector and

the mean standard deviation of the noise, providing a qualification of how good is the separation between signal and background noise. It is computed via

$$N_{\sigma} = \frac{\phi_{Ch} \cdot A \cdot \Omega \cdot T \cdot \tau \cdot q_E}{\sqrt{\phi_{NSB} \cdot A \cdot \Omega \cdot T \cdot \tau \cdot q_E}},$$
(5.1)

where A is the detector's collection area, Ω is the solid angle corresponding to the field of view of the apparatus, T is the atmosphere's transmission coefficient (as discussed in chapter 3), τ is the collection time, q_E is the quantum efficiency of the electronics, and ϕ_{Ch} and ϕ_{NSB} are the Cherenkov and night sky background fluxes, respectively. In the following table are presented the values selected for those parameters, regarding the Fluorescence Detector at Pierre Auger.

Table 1 – Selected values for computation of N_{σ}

Parameter	Value
А	$3.8 \ [m^{-}2]$
Ω	$1.95 \; [\rm{deg}^2]$
au	50 [ns] or 100 [ns]
q_E	0.25
ϕ_{NSB}	$40 [\mathrm{m}^{-2} \mu \mathrm{s}^{-1} \mathrm{deg}^{-2}]$

Source: By the author

5.3.2 Trigger simulation

There is a difference between photons arriving at the telescope and a signal being detected. First, the incoming photon promotes the emission of an electron in the Photon-cathode of a photomultiplier tube, PMT, followed by the multiplication of electrons in the dynode, resulting in over a million electrons. These electrons then form a current which is converted into a digital signal through the analog-to-digital converter. Depending on the digital processor used, the signal is collected in different time bin sizes (the already mentioned collection time). Those *time bins* containing the number of measured photo-electrons can then be evaluated as a single event. The quantum efficiency on the photo-electron conversion is embedded in the N_{σ} calculation.

The night sky background is the sum of all light contributions which are not from the desired events, such as moonlight, stars, comets, and man-made light. It is slowly varying in time as compared to the cosmic rays events so that it can be measured throughout the night and subtracted from the signal computed by the telescope. In this work, we consider a good event signal when, after the subtraction of the noise value,



Figure 18 – Illustrative example of the signal-to-noise ratio value for each time bin, detected at a telescope 50 meters away from the shower core. The incidence angle is $\theta = 40^{\circ}$ and the primary iron energy is $E = 10^{16}$ eV. This is the same event depicted in Figure 17, with the values of N_{σ} calculated via Equation 5.1.

the resulting signal is at least three times greater than the noise standard deviation. As previously mentioned, this ratio is known as the signal-to-noise ratio, N_{σ} . In Figure 18 we observe the N_{σ} values for each time bin in an event.

Therefore, apart from the successful events we also have to distinguish the *triggered* events, i.e., those among the successful which have at least one temporal bin with a signal-to-noise ratio greater than or equal to three. In the next chapter, we study in greater detail those triggered events.

6 RESULTS AND DISCUSSIONS

Now that the simulation procedure is understood, along with the adopted simplifications, the reader is provided with physical information regarding the simulations such as memory usage and run time. This is presented in section 6.1.

In the second section, we discuss the rate of successful simulated events along with the trigger criterion, which is understood as the expected percentage of triggered events. This is done in the context of the Pierre Auger Observatory.

In section 6.3 we interpret the simulations in the context of the Pierre Auger Observatory, obtaining the expected number of events per year. We consider different iron composition scenarios from the all-particle flux measured by the Auger Observatory (subsection 6.3.1), and also evaluate the iron flux resulting from detection of several other experiments (subsection 6.3.2).

6.1 Production of a shower library

The simulations were run in the Santos Dumont supercomputer, located at the headquarters of the National Laboratory for Scientific Computing (LNCC/MCTI, Brazil). The supercomputer has a processing capacity of approximately $5, 1 \times 10^{15}$ float-point operations per second. The computing capacity is a result of over thirty four thousand Central Process Units, CPUs, arranged in several computing nodes. According to the needed processing capacity, the user requests a number of nodes to perform the desired task; the number of nodes is associated to a run time limit for each submitted process.

Given the constraint on simulation time when using a shared cluster, it was necessary to impose a limitation on the number of simulated events. We have imposed a fixed number of *successful events*: those which have at least one photon arriving at the telescope's location. However, knowing that not all simulated events are *successful*, we have kept track of the success rate: the percentage out of all simulated events which are successful. We have run 2 sets with 1000 successful primary iron events for each configuration^{*}.

^{*} A configuration consists on a combination of energy value, in the range of 10¹⁶ to 10²⁰ eV in steps of two orders of magnitude; a zenith angle value, in the range of 40 to 80^o in steps of 20^o; and a core distance value, the values being dependent on the selected zenith angle.

In Figure 19, we present the success rate values as a function of core distance for an incidence of 40° , we can observe a general behavior on diminishing success rates with greater distances from shower core to the telescope center. That behavior is also seen in Figure 20, related to a different incidence angle. We can infer that the diminishing success rate is a consequence of a larger area over which the Cherenkov photons shall be distributed, therefore diminishing the probability of a photon arriving at a fixed size target such as the telescope.

For the simulations regarding this work, a total of 170 hours using 24 computing nodes were required. This guaranteed 2000 successful primary iron events for several configurations. From those, 26 hours were related to events with a zenith angle value of 80°, which were later discarded for not resulting in any triggered event. Those configurations with less than 2000 simulated events were disregarded during the analysis.

The memory usage amounts to 5.3 Gb, being reduced to 4 Gb after the disposal of aforementioned events. The small allocation of memory was possible due to the election of the high compression binary output form in ROOT files † .

 $^{^{\}dagger}$ For more information please refer to https://root.cern.ch/save-data



Figure 19 – Success rates of all simulated events for Iron primary as a function of shower core to telescope distance, incidence of 40°. Each color represents a primary energy. On the top panel, values for the first run of simulations providing 1000 successful events for each configuration, and on the bottom panel, values for the second run.



Figure 20 – Success rates of all simulated events for Iron primary as a function of shower core to telescope distance, incidence of 60°. Each color represents a primary energy. On the top panel, values for the first run of simulations providing 1000 successful events for each configuration, and on the bottom panel, values for the second run.

6.2 Trigger efficiency

We have evaluated each successful event and observed that, on more than 80% of those, there is only one triggered time bin. This behavior can be noticed in Figure 21, Figure 22, and Figure 23 where the percentage of all simulated events is shown as a function of the number of consecutive triggered time bins. In those figures, on the left panel the primary energy is 10^{16} eV, on the right panel the primary energy is 10^{18} eV, and on the bottom panel the primary energy is 10^{20} eV. In Figure 21 the incidence angle is $\theta = 40^{\circ}$ and the telescope's collection time is 50 ns; in Figure 22 the collection time is also 50 ns but the incidence in $\theta = 60^{\circ}$ while on Figure 23 the inclination of the shower is the same as the previous but the collection time is 100 ns. The difference in collection times comes from the two possible detectors for a corresponding elevation of 30° : HEAT and FD have the aforementioned collection times, respectively.

Focusing on those successful events with one temporal bin abiding the signal-to-noise criterion, we have computed the percentage of all simulated events which are detectable, therefore taking into consideration both the success rate and the trigger criterion. This can be observed in Figure 24, where the percentage of triggered events as a function of energy is shown for zenith angles of 40° , on the left, and 60° on the right. Top panels refer to 50 ns collection time while the bottom panel refers to 100 ns collection time and 60° incidence angle.

Figure 24 provides the expected percentage of events, at corresponding energy and zenith angle, which should give origin to a reliable signal at HEAT and FD detectors. We can translate that in the expected number of triggered events per year at the Pierre Auger Observatory. This is achieved in the next section.



Figure 21 – Distribution of events according to the number of consecutive triggered time bins of 50 ns for Iron primary, incidence of 40°. Each color represents a distance from the shower core to the telescope, from 25 to 150 meters in steps of 25 meters. On the left panel, primary's energy is $E = 10^{16}$ eV, on the right panel, $E = 10^{18}$ eV, and on the bottom panel, $E = 10^{20}$ eV.



Figure 22 – Distribution of events according to the number of consecutive triggered time bins of 50 ns for Iron primary, incidence of 60°. Each color represents a distance from the shower core to the telescope, from 50 to 300 meters in steps of 50 meters. On the left panel, primary's energy is $E = 10^{16}$ eV, on the right panel, $E = 10^{18}$ eV, and on the bottom panel, $E = 10^{20}$ eV.



Figure 23 – Distribution of events according to the number of consecutive triggered time bins of 100 ns for Iron primary, incidence of 60° . Each color represents a distance from the shower core to the telescope, from 50 to 300 meters in steps of 50 meters. On the left panel, primary's energy is $E = 10^{16}$ eV, on the right panel, $E = 10^{18}$ eV, and on the bottom panel, $E = 10^{20}$ eV.



Figure 24 – Distribution of triggered events in the universe of all simulated events as a function of iron primary energies. Each curve represents a distance from shower core to the telescope. On the left, the incidence angle of the primary is $\theta = 40^{\circ}$, on the right $\theta = 60^{\circ}$, and on the bottom $\theta = 60^{\circ}$ but with a collection time of 100 ns.

6.3 Expected number of triggered events at the Pierre Auger Observatory

We are interested in the number of events per year, so one must integrate the flux over the collection area, the field of view, and energy range. Since our simulations were specifically for a primary iron nucleus, we must observe the iron spectrum in the desired energy range. We refer to Rújula (2) in subsection 6.3.2 and to the Pierre Auger collaboration (35) in subsection 6.3.1, by considering in the all particle flux different concentrations of iron nuclei.

Since the DC photons only arrive at the telescope when the shower axis is in front of the telescope, the area where a shower core can arrive and the photons are detected corresponds to a fraction of the area of a circle centered at the telescope. Since the horizontal angular aperture of the telescopes is 30°, it corresponds to $\frac{1}{12}$ of a full circle, 360°, and therefore the corresponding area is $\frac{1}{12}$ of the total area of a circle. As before, we evaluate three scenarios: $\theta = 40^{\circ}$ and collection time $\delta t = 50 \text{ ns}$, $\theta = 60^{\circ}$ and $\delta t = 50 \text{ ns}$, and $\theta = 60^{\circ}$ and $\delta t = 100 \text{ ns}$. When considering $\delta t = 50 \text{ ns}$, we are in the HEAT scenario, where each of the 3 telescopes has a field of view of $30^{\circ} \times 30^{\circ}$, with elevation starting at 30° . In the FD scenario, there are 24 telescopes with a collection time of 100 ns and field of view of $30^{\circ} \times 30^{\circ}$, with elevation starting at 1.5° . Since each PMT has an angular aperture of $1.5^{\circ} \times 1.5^{\circ}$, and recalling all photons are collected by a single PMT, each telescope is considered to have a total aperture of $1.5^{\circ} \times 30^{\circ}$ for a given zenith.

In the following table, we can see the values of the area and solid angle, Ω , adopted for HEAT and FD scenarios.

	Area	Ω
FD	$24 \times \frac{1}{12}\pi R^2 = 2\pi R^2$	$24 \times 45 \ \mathrm{deg^2} = 0.32898636 \ \mathrm{sr}$
HEAT	$3 \times \frac{1}{12} \pi R^2 = \frac{1}{4} \pi R^2$	$3 \times 45 \ \deg^2 = 0.041123293 \ sr$

As can be seen in Figure 24, besides the dependence on energy, the expected number of detected events is highly dependent on the shower core distance to the telescope. We have opted to compute the area in rings, centered at the telescope and corresponding to the simulated values for the core distance R. For example, we consider the percentage of detected events to be constant between R = 0 and R = 50 m, corresponding to an area of $a_{50} = \pi (50^2 - 0^2)$ m²; it is also constant between R = 50 and R = 100 m, corresponding to an area of $a_{100} = \pi (100^2 - 50^2)$ m²; and so on. Therefore, when computing the number of detected events, it is scaled proportionally to the expected percentage, P_i , of all possible events according to the core distance. In a nutshell, P_i is a consequence of both the success rate and the fraction of events with $N_{\sigma} \geq 3$, which can be observed in Figure 24. The total area A_i depends on the type of detector, being $A_i = 2a_i$ for FD and $A_i = \frac{1}{4}a_i$ for HEAT, as proposed in the table above. The tables for corresponding values of P_i and A_i can be found in Appendix B and Appendix C, respectively.

6.3.1 Iron flux estimated from the all-particle spectrum measured by the Pierre Auger Observatory

The Pierre Auger Observatory has long been taking data and contributing to the Ultra High Energy Cosmic Rays spectrum, UHECRs, which corresponds to those particles and nuclei arriving at Earth with energies greater than few 10^{18} eV. As discussed in section 4.2, the observatory's measurements featuring the hybrid detection mode have recently allowed lowering the energy threshold to $10^{16.5}$ eV.

On the other hand, the composition of UHECR is still not well known, since the inference of composition via air shower measurements is highly dependent on the chosen hadronic interaction model. Therefore, we have opted to explore different scenarios of iron concentration on the all-particle flux of primaries, as to have a prediction of the detectability of direct Cherenkov radiation in each scenario.

Here we take into account the reported measurements from Pierre Auger, represented by the full circles in the right panel of Figure 25 representing the measured all-particle flux of cosmic rays. From this graph, we adopted the following approximate values for the differential spectrum Φ : $E^3 * \Phi(E = 10^{16} eV) = 8 \times 10^{37} [\text{km}^{-2} \text{ yr}^{-1} \text{ sr}^{-1} \text{ eV}^2]$; $E^3 * \Phi(E = 10^{18} eV) = 6 \times 10^{37} [\text{km}^{-2} \text{ yr}^{-1} \text{ sr}^{-1} \text{ eV}^2]$.

From that, we assume 4 possible scenarios, corresponding to the following concentrations of Fe nuclei: 100%, 75%, 50%, and 25%. The expected number of detected events per year can be seen in Table 2.

We can observe that even for the lowest concentration of 25% of iron in the primary cosmic rays, the expected number of events per year is still experimentally relevant for the primary energy of 10^{16} eV.



Figure 25 – Spectrum of primary cosmic rays, scaled by E^3 as a function of primary energy. On the left panel, markers represent different measurement techniques from Pierre Auger, while on the right panel the combined data is presented by full circles. For more information, refer to 1.

Source: THE PIERRE ... (1)

Table 2 – Expected number of triggered events per year according to the primary energy and iron nuclei concentration on the all-particle spectrum measured by the Pierre Auger Observatory. On the top table, values for the HEAT detector considering the zenith angle values $\theta = 40^{\circ}$ and $\theta = 60^{\circ}$. On the bottom table, values for the FD detector considering the only visible zenith angle values $\theta = 60^{\circ}$. For the HEAT detector, the collection time is 50 ns, while for FD it is 100 ns.

HEAT

E [eV] Detector	10 ¹⁶		10 ¹⁸	
	$\theta = 40^{o}$	$\theta = 60^{\circ}$	$\theta = 40^{\circ}$	$\theta = 60^{\circ}$
100% Fe	69	16	6.6×10^{-3}	1.6×10^{-3}
75% Fe	52	12	4.9×10^{-3}	1.2×10^{-3}
50% Fe	35	8	$3.3 imes 10^{-3}$	$8.0 imes 10^{-4}$
25% Fe	17	4	$1.6 imes 10^{-3}$	$4.0 imes 10^{-4}$

 FD

E [eV] Detector	10^{16}	10^{18}
100% Fe	1207	1.1×10^{-1}
75% Fe	905	$8.0 imes 10^{-2}$
50% Fe	604	5.4×10^{-2}
25% Fe	302	2.7×10^{-2}

6.3.2 Iron flux estimated from the all-particle spectrum measured by several experiments

We can also obtain the expected number of triggered events by evaluating data collected by other experiments. In Figure 26 we observe the flux of iron nuclei as measured by several experiments, from which we obtained the following values for $\Phi: E^{2.5} * \Phi(E = 10^{16} eV) = 4 \times 10^2 [\text{m}^{-2} \text{ s}^{-1} \text{ sr}^{-1} \text{ GeV}^{1.5}]$; $E^{2.5} * \Phi(E = 10^{18} eV) = 4 \times 10^1 [\text{m}^{-2} \text{ s}^{-1} \text{ sr}^{-1} \text{ GeV}^{1.5}]$. From these values and considering the different detection possibilities, namely the incidence angle and energy from the primary in combination with the detector being FD or HEAT, we estimated the expected number of detected events by the Pierre Auger Observatory. The number of events per year can be seen in Table 3. For the zenith angle $\theta = 40^{\circ}$, the events are only visible to the HEAT detector. The differences which arise from distinct detectors are related to the number of telescopes constituting each detector and the collection times of those, as discussed in chapter 4.

Table 3 – Expected number of triggered events per year as a function of the primary energy and detector, according to the iron nuclei concentration on the all-particle spectrum measured by several experiments and depicted in Figure 26. For the HEAT detector, the collection time is 50 ns, while for FD the collection time is 100 ns.

E [eV] Detector	10 ¹⁶		10 ¹⁸	
	$\theta = 40^{o}$	$\theta = 60^{\circ}$	$\theta = 40^{\circ}$	$\theta = 60^{\circ}$
HEAT	35	8	3.3×10^{-3}	8.0×10^{-4}
FD		602		$5.3 imes 10^{-2}$

Source: By the author

It is clear that for the lower simulated energy the results are more satisfactory. We should mention that the flux is not measured directly in the energy range used in the simulations, therefore it is dependent on high energy interaction models since the values are obtained by the observation of extensive air showers. As a consequence, the iron flux shown in Figure 26 is a result, for energies greater than a few hundred TeV, of the interpretation of data from air shower experiments taking into account interaction models. (36)



Figure 26 – Spectra of p, He, Fe, and CNO primary cosmic rays, scaled by $E^{2.5}$. Markers represent measurements from several experiments, while continuous and dotted lines refer to acceleration models predictions on the spectra. For more information on the models, the reader may refer to 2.

Source: RÚJULA. (2)
7 CONCLUSIONS

In this work we have studied the emission of direct Cherenkov photons, which are sensitive to the primary CR charge and to the varying refractive index of the atmosphere. The main objective was to investigate the detection prospect of DC photons using the fluorescence telescopes at the Pierre Auger Observatory.

We simulated the production of DC photons, as well as their propagation through the atmosphere, using the Monte Carlo inverse transform method and an atmosphere model. We wrote a simplified simulation of the telescopes to estimate the detectability of such photons in the presence of night sky background.

Considering the analysis done so far, we observe that the greater number of telescopes associated with the FD detector is a decisive factor, providing a greater expected number of detected events per year, as can be seen by comparing the lines for each table presented in Table 3 and Table 2.

The sampling time of the telescope also plays a role in the number of expected events with at least one time bin presenting a signal-to-noise ratio greater than or equal to 3, as can be seen by comparing Figure 22 and Figure 23.

Even though our simulation consists of a small sample of events, which were obtained using several simplifications (such as the selection of one empirical discrete atmosphere model, the disregard of energy losses by the primary, the independence of wavelength on the refractive index of air, and so forth) and errors which were not accounted for due to the Monte Carlo method, the results point to the possibility of detection of Cherenkov radiation produced by the passage of primary cosmic iron through the atmosphere by using the already functioning fluorescence telescopes at Pierre Auger. The prospect of detection of direct Cherenkov radiation is in accordance with the detection by some experiments using IACTs such as VERITAS. (5)

We can observe a tendency of a greater expected number of detected events at lower energies. We cannot, however, predict the dependence of detected events as a function of inclination for a given energy, since we have only investigated two such values. Therefore, it would be valuable to investigate other combinations of energies and zenith angles.

From all the simulated events with an inclination of $\theta = 80^{\circ}$, none presented a signal-to-noise ratio greater than or equal to 3, hence they were not included in the results.

From the inspection of the above tables providing the expected number of detected events per year at the Pierre Auger Observatory, one can observe that an increase in two orders of magnitude in the energy results in a decrease of almost four orders of magnitude in the number of detected events per year. Assuming a similar behavior for energies higher than the simulated ones, we can infer that no events would be observed by the detection of DC light using the telescopes at Pierre Auger.

We observed a general behavior of greater detectability of events at lower energy. The simulated energy of 10^{16} eV, however, is to this date not measurable by the Pierre Auger observatory, which has only recently lowered the energy threshold for detection to $10^{16.5}$ eV by using Cherenkov dominated events in the fluorescence detector. (1) This encourages us to further investigate the topic.

It is important to point out some possible enhancements to this study: a continuous description of the atmosphere, a more refined Cherenkov photons production model, the usage of Pierre Auger's software to simulate telescope response, Monte Carlo simulations of whole extensive air shower to evaluate signal separability^{*} and the simulation on even lower energies.

^{*} i.e., if the direct Cherenkov photons are distinguishable from photons from the shower. This in principle could be done either temporally or by evaluating the signal at neighboring PMTs.

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Appendix

APPENDIX A - MUON CONTENT ON GAMMA INITIATED SHOWERS

In the next few years, it is expected the construction and inauguration of the *Cherenkov Telescope Array* - CTA - in its Southern site, to be located in Chile. The observatory will use Imaging Air Cherenkov Technique - IACT - to investigate Gamma-Ray Sources by pointing Telescopes at astrophysical objects. The range of energy of such Gamma Rays is expectedly from 10^9 eV to 10^{14} eV.

Since the proton events in this range of energy are much more common than the γ Ray ones, it is necessary to identify them as composing the background for gamma events. Even though the Hillas parameters together with stereo reconstruction parameters allow for a decent * γ /hadron separation, there are still proton-initiated showers being detected as gamma-initiated showers, which are called *gamma-like* showers.

Maier e Knapp(37) have demonstrated that the transfer of energy to the electromagnetic component (which dominates in γ showers) is mainly due to the production of highly energetic neutral pions (π^0) and eta mesons (η) since those particles decay onto two photons [†]. In 37, we learn that "about 50% of the relevant particle production occurs in or shortly after the first interaction".

With this in mind, our idea was to contribute with this analysis by identifying those showers initiated by a hadron but accused by the current data analysis to be initiated by a photon. The scenario investigated depicts a high electromagnetic component resulting from the decay of a neutral pion. For that, we investigated the production of a high energy π^0 in the first interaction of the Cosmic Ray with the atmosphere.

Firstly we investigated the distribution of the fraction of energy carried by a neutral pion in the interaction of a proton with a Nitrogen atom [‡]. By simulating a set of 100000 events with the Cosmic Ray Monte Carlo software we obtained the distribution seen in Figure 27, where the N atom was considered to be at rest while the proton Cosmic Ray with varying energies from 10 TeV to 100 TeV in steps of 10TeV.

From that, we could notice that on only 3% of the interactions the produced neutral pion was the most energetic secondary particle arising from this collision, being the so-called *leading particle*. In addition, the evaluation of those distributions showed that this leading π^0 carries on average 30% of the proton's energy.

Then, we carried simulations using the CORSIKA software in order to evaluate

^{*} According to Maier and Knap, for point-like sources, image shape and shower direction cuts typically suppress the background by a factor of 2000. (37)

[†] Branching ratios of $(98.823 \pm 0.034)\%$ and $(72.12 \pm 0.34)\%$, respectively

^{\ddagger} The most abundant atom in our atmosphere, corresponding to almost 70% of its content.



Figure 27 – Distribution of neutral pions produced in first interaction of a primary proton with atmospheric Nitrogen atom, according to fraction of primary's energy carried.

Source: By the author

the lateral distributions of muons and Cherenkov photons, since those are measurable components of an extensive air shower. We expected the Cherenkov lateral profile to be similar to that of a gamma-initiated shower, but the muon content to be high enough to be distinguish both scenarios due to the early development of an electromagnetic cascade with a reminescent of a hadronic component.

A set of 1000 simulations for each gamma- and proton-initiated events were performed. Since the avarage energy carried by the neutral pion corresponds to about 30% of the proton's energy, the comparison was made between the showers of a 10 TeV primary proton and a 3 TeV primary photon.

In Figure 28 we can see that, as expected, the gamma-like showers are similar to gamma-initiated showers, evident for the presence of a "Cherenkov pool": the increase in Cherenkov photons density around 120 m from the shower core (38).

From Figure 29 we understand that even though the muon distribution in the gamma-like scenario is similar to the hadronic shower while distinct to the gamma cascade, its density at the ground level of 1400 m.a.s.l. is too low to allow detectability. In other words, the lack of detection of a muon (from a regular sized muon detector, $5m^2$) does not guarantee the occurrence of a photon-initiated shower, hence the employment of muons



Figure 28 – Average Cherenkov photons' density as a function of the distance from shower's core. The red line represents the distribution for a 10 TeV proton-initiated usual shower; the blue line represents the scenario where a leading neutral pion is produced in the first interaction of a 10 TeV proton with the atmosphere; the green line represents de 3 TeV gamma-initiated shower.

Source: By the author

detectors does not provide the identification of gamma-like proton events as background for the gamma events in this energy range.



Figure 29 – Average density of muons at altitude of 1400 m.a.s.l. for each type of shower. The red line represents the distribution for a 10 TeV proton-initiated usual shower; the blue line represents the scenario where a leading neutral pion is produced in the first interaction of a 10 TeV proton with the atmosphere; the green line represents de 3 TeV gamma-initiated shower.

Source: By the author

Table 4 – Expected percentage of all possible events which have one temporal bin with $N_{\sigma} > 3$, P_i , according to the core distance and primary energy. On the left side, the zentih angle is $\theta = 40^{\circ}$ and the sample time is 50 ns while on the right $\theta = 60^{\circ}$ and the sample time is also 50 ns. On the bottom table, $\theta = 60^{\circ}$ and the sample time is 100 ns.

$\theta =$	$40^{\circ},$	δ	$= 50 \mathrm{ns}$	
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E [eV] R [m]	10^{16}	10^{18}
25	0.1342460	0.1348160
50	0.3942770	0.4256200
75	0.2842640	0.2752690
100	0.1446420	0.1261730
125	0.0479350	0.0402080
150	0.0100590	0.0078805

 $\theta = 60^{o}, \ \delta = 50 \, \mathrm{ns}$

E [eV] R [m]	10^{16}	10^{18}
50	0.00026013	0
100	0.0159508	0.0155390
150	0.0143442	0.0161967
200	0.0111344	0.0093305
250	0.0041933	0.0044439
300	0.0015372	0.0012905

 $\theta = 60^{\circ}, \ \delta = 100 \,\mathrm{ns}$

E [eV] R [m]	10^{16}	10^{18}
50	0	0
100	0.0121530	0.0107930
150	0.0191992	0.0181148
200	0.0173630	0.0108234
250	0.00635616	0.0049803
300	0.00183578	0.0014326

Source: By the author

Table 5 – Annuli areas, a_i , for intervals of simulated core distance from telescope, R. On the left values of R corresponding to $\theta = 40^{\circ}$, on the right $\theta = 60^{\circ}$.

$\theta = 40^{\circ}$		
$a_i [\mathrm{m}^2]$		
1963.49		
5890.49		
9817.48		
13744.47		
17671.46		
21598.45		

$\theta = 60^{\circ}$		
	range [m]	$a_i [\mathrm{m}^2]$
	0 - 50	7853.98
	50 - 100	23561.94
	100 - 150	39269.91
	150 - 200	54977.87
	200 - 250	70685.83
	250 - 300	86393.80

Source: By the author