COSMIC RAYS AIR SHOWERS PROPERTIES AND CHARACTERISTICS OF THE EMITTED RADIO SIGNALS USING ANALYTICAL APPROACHES AND FULL MONTE CARLO SIMULATIONS

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Received July 2, 2019

Abstract. Cosmic rays have been a hot topic for the Astroparticle Physics community, since discovered in 1912. After over a century and many efforts from scientists worldwide we know now that the most energetic particles observed on Earth, the ultra-high energy cosmic rays (UHECRs), have an extragalactic source. Where, how and what exactly accelerates them? These questions remain still mysterious nowadays.

The extensive air showers (EAS) developed by cosmic rays (CRs) in the Earth’s atmosphere are at this moment the most resourceful subject of study for researchers who make efforts to better understand these fascinating particles. However, the detection and study of EAS is not at all an easy task. Because the Earth’s atmosphere is being used as a giant detector of cosmic rays, EAS develop differently based on primary particle energy and mass, incoming direction and atmospheric environment at a given location.

In this paper we look at the development of EAS from two different, but complementary perspectives. First, we show how the main parameters of the showers modify, as function of the primary properties, by multiple longitudinal profiles simulated with CONEX, for different sets of CR parameters (energy, mass, direction of propagation). Next, we look at the radio signals emitted by EAS, which develop at the Pierre Auger Observatory location, by using a simplified $\vec{v} \times \vec{B}$ model to describe the geomagnetic emission, and sophisticated simulations with the CoREAS option in the CORSIKA Monte Carlo code, who treat the full radio emission released by an air shower. Some of the results presented in this paper are included in an open source graphical user interface (GUI) application, EAS Browser v2.0.

Key words: cosmic rays, air showers, radio emission, graphical user interface.

1. INTRODUCTION

Every day we live in a medium surrounded by a natural fond of radiation. The cosmic radiation was first discovered by Victor Hess in 1912 when he flew in a balloon and measured the ionization of the air up to altitudes of 5 km. In his experiment Hess was trying to determine the penetration power of the gamma rays, from the natural radiation, that were believed to be responsible for the processes of the air ionisation. Hess was expecting that with a higher altitude the ionization will drop,
but the measurements where showing an unexpected increase of the ionization rate. The only explanation he found was a highly penetrating radiation that enters in the atmosphere from above. These particles have been named cosmic rays.

The Earth is continuously being bombarded by cosmic rays. They have a wide spectrum of energies, from below $10^9 \text{eV}$ up to $10^{21} \text{eV}$, and mass composition, from the lighter nuclei of Hydrogen or Helium, to the heavier Iron nuclei. If cosmic rays with energies up to $10^{15} \text{eV}$ are now well documented and understood, the most energetic ones, the ultra high energy cosmic rays (UHECRs), which possess energies way over the limit of the largest particles accelerator on Earth (Large Hadron Collider — 14 TeV), are still a subject of debate. The main problem is however the very small flux of the UHECRs on Earth, i.e. at energies over $10^{19} \text{eV}$ the flux rate is of about one particle per $km^2$ per century. For this reason, giant areas of detection like the Pierre Auger Observatory (3000 $km^2$) were build and the extensive air showers which are initiated by the cosmic rays in the Earth’s atmosphere have become the most important subject of study for scientists who work in this domain.

After many years of hard work, researchers from the Pierre Auger Collaboration where able to confirm that the UHECRs have an extragalactic origin [1], but what astrophysical events can generate them and how can they reach these energies is still a mystery.

In the first part of this paper we show how properties of EAS modify with parameters of the primary particle by using an analytical parametrization [2] and CONEX simulations [3, 4]. In the second part we introduce a simplified $\vec{v} \times \vec{B}$ model based on the Lorentz force [5] and compare the obtained results with full CoREAS simulations [6].

2. EAS PROPERTIES

When cosmic rays enter in the Earth’s atmosphere they interact and develop cascades of elementary particles called extensive air showers (EAS). The development of an EAS is strongly correlated with the parameters of the primary cosmic ray (mass, energy and direction of propagation) and so is very important to have a clear understanding of the EAS properties. Some of these properties can be easily observed from the longitudinal profiles of the showers, which are presented further.

2.1. ANALYTICAL PARAMETRIZATIONS

At first lets take a simple case of a purely electromagnetic shower which develops vertically in the atmosphere. For an electromagnetic shower to develop, it is necessary to be initialized by an electromagnetic interaction in the atmosphere and the primary particle will be either an $e^-$, $e^+$ or $\gamma$. This EAS can very well be de-
scribed by an analytical parametrization dating back to 1956, introduced by Greisen [2]. Two parameters are of interest, the shower age (Fig. 1) and the total number of charged particles developed in the shower (Fig. 2), which are calculated for different primary energies, in the range of $10^{17} - 10^{21} \text{eV}$.

**Fig. 1:** Shower age distribution over the atmospheric depth, being 0 at the first interaction and about 1 at the maximum of shower development.

**Fig. 2:** Total charged particle distribution over the atmospheric depth.

The shower age ($s$), gives information about the development stage of the shower and it can be written as a function of the atmospheric depth (Eq. 1).

$$s(X) = \frac{3X}{X_0} + 2 \ln \left( \frac{E_p}{E_{crit}} \right)$$

(1)
The total number of charged particles developed in the shower (N), can also be written as a function of the atmospheric depth, according to Eq. 2,

\[ N(s) = \frac{0.31 \exp \left( \left( \frac{X}{X_0} \right)(1 - \frac{3}{2} \ln s) \right)}{\sqrt{\ln \left( \frac{E_{\text{crit}}}{E_{\text{crit}}} \right)}} \]  

where \( X_0 = 36.7 \) g/cm\(^2\) is the electron radiation length in the air and \( E_{\text{crit}} = 86 \) MeV is the critical energy of the electrons in the atmosphere, which can be defined as the threshold energy where the ionization losses are equal to the radiation losses of electrons moving through air. From the results of this parametrisation illustrated in the Figs. 1 and 2, one can observe that cosmic rays with higher energies initiate showers which develop deeper in the atmosphere and generate more secondary particles.

2.2. CONEX SIMULATIONS

The major components of an EAS, muonic, hadronic, and electromagnetic, are illustrated in Fig. 3. By looking at the longitudinal profiles of these components simulated with CONEX [4] for different primary energy and type of the incident particle one can observe different characteristics of the shower, such as the number of secondary particles rise with primary particle energy and mass (Figs. 4a, 4b), maximum development of the shower varies with mass of the primary (Figs. 4c.

Fig. 3 – Illustration of an EAS with its major components: electromagnetic, muonic and hadronic [7].
4d), and the number of secondary particles that reach the ground depends on the inclination angle of the shower (Figs. 4e, 4f).

An EAS initiated by a CR with a smaller mass and a higher energy will reach its maximum development point deeper in the atmosphere. More information about the primary particle mass can be extracted from the number of muons developed by an EAS. As it can be observed in Fig. 4d, showers initiated by CRs with greater masses develop more muons and because this component is highly penetrating, the vast majority of the muons will reach the surface of the Earth and will be detected by ground detectors as the Cherenkov water tanks from the Pierre Auger Observatory.

Vertical showers, compared with the inclined ones (zenith \( \theta \geq 60^\circ \)), tend to develop faster in the atmosphere and have a rather short life time, as it can be seen in Figs. 4e, 4f. In contrast, particles from an inclined shower meet a less dense medium on their path and thus more particles will reach the ground.

3. RADIO EMISSION

Radio emission is one of the processes developed during the evolution of an extensive air shower. The geomagnetic effect is considered the dominant contribution in the radio emission process, while the negative charge excess developed in the shower front may contribute significantly, depending on the geometry of the shower and the position of the observer with respect to the shower core. Polarization characteristics of the radio signals are important aspects in verifying the radio emission mechanisms [8]. Issues of shower geometry related to polarization effects will be discussed in this paper.

3.1. \( \mathbf{v} \times \mathbf{B} \) MODEL

While charged particles in the shower body are deflected in the Earth’s magnetic field, the geomagnetic emission is being produced giving rise to radio signals. In a first order approximation [5], the geomagnetic emission can be understood by the Lorentz force model, \( i.e. \) the cross product vector \( \mathbf{v} \times \mathbf{B} \), where \( \mathbf{v} \) represents the incoming shower direction and \( \mathbf{B} \) the Earth’s magnetic field at a certain location [9] \( e.g. \) Pierre Auger Observatory in the Southern Hemisphere, \( \theta_B = 55^\circ \), \( \varphi_B = 90^\circ \).

\[
P_{EW} = |\mathbf{v} \times \mathbf{B}|_{EW} = \sin \theta \cdot \sin \varphi \cdot \cos \theta_B - \cos \theta \cdot \sin \theta_B \cdot \sin \varphi_B; \tag{3}
\]

\[
P_{NS} = |\mathbf{v} \times \mathbf{B}|_{NS} = \sin \theta \cdot \cos \varphi \cdot \cos \theta_B - \cos \theta \cdot \sin \theta_B \cdot \cos \varphi_B \tag{4}
\]
In Fig. 5 it is shown that for showers coming from North and South directions, one can get maximum signals in East and West polarization channels (in this case the projected cross product vector towards the EW direction, Eq. 3), while for showers coming from the East and West directions, one can get maximum signals recorded in the North and/or South channels of a detector (i.e. the NS projection of the cross product vector, Eq. 4), depending on the geomagnetic position of the experiment lo-

(a) Primary energy and mass dependency of the electromagnetic component.

(b) Primary energy and mass dependency of the muonic component.

(c) EAS electromagnetic profiles for different primary energies at $10^{19}\text{eV}$.

(d) EAS muonic profiles for different primaries at $10^{19}\text{eV}$.

(e) EAS electromagnetic profile fluctuations with the zenith angle for proton at $10^{19}\text{eV}$.

(f) EAS muonic profile fluctuations with the zenith angle for proton at $10^{19}\text{eV}$.

Fig. 4 – CONEX simulated air showers profiles for different parameters of primary cosmic rays.
Fig. 5 – Skymaps of showers coming from EW (left panel) and NS (right panel) directions, as function of all range of azimuth and zenith = 0 - 80 degrees, color coded by amplitude.

cation (e.g. at the Pierre Auger Observatory one can get maximum signal for showers coming from the South, i.e. the opposite direction of the geomagnetic angle). This is a note that the geomagnetic emission, which is linearly polarized, is perpendicular to the shower axis and the Earth’s magnetic field.

Fig. 6 – Rotated axes (x,y) of the cross product vector for different zenith angles.
By rotating the two NS and EW polarization components of the radio signals with the polarization angle $[10]$, i.e. the angle between x and y axis of the cross product vector, signal recorded in the NS channel ($y'$-axis, Eq. 6) cancels, and the geomagnetic contribution of the signal goes to the EW channel only ($x'$-axis, Eq. 5), as seen in Fig. 6.

\[ x' = x \cos \phi_{mag} + y \sin \phi_{mag} \]  
\[ y' = -x \sin \phi_{mag} + y \cos \phi_{mag} \]  

Fig. 7 - Comparison between the NS and EW polarization ratio of the $\vec{v} \times \vec{B}$ amplitude and the ratio of simulated amplitude with CoREAS.
3.2. COREAS SIMULATIONS

Variations of negative charge-excess developed in the shower partially leads to the radio emission process, i.e. the Askaryan effect. It implies the radial polarization dependence on the position of the observer with respect to the shower axis.

For a sample of eight simulated events (e.g. a primary proton at $10^{18}$ eV, with a zenith of 70 degrees, as well as various observers on a radius up to 500 m from the shower core are considered), in Fig. 7 is shown a comparison between the $\vec{v} \times \vec{B}$ model and CoREAS simulations [6], from which one can clearly see a major correlation with the exception of few events coming from the N and S directions. This so-called "side effect" observed can be associated to the Askaryan effect, additionally to the main geomagnetic contribution in the radio emission process of air showers.

While for the geomagnetic emission the azimuth angle, respective the geomagnetic angle formed by the showers axis and the Earth’s magnetic field, are correlated, for the Askaryan effect there are two additional angles which play an important role, the polarization angle and the observer angle between the x-axis (EW polarization) and the axis defined by the shower core and the observer position [10, 11].

![Graph showing percentage contribution of each polarization](image)

Fig. 8 – The average percentage contribution of each polarization in the signal for a sample of 8 events as comparison between model and simulations. The error bars represent the deviation of the signal registered in each polarization channel at each individual antenna, reported to the amplitude recorded by all antennas per event.
3.3. DISCUSSIONS

In comparison of the simplified $\vec{v} \times \vec{B}$ model with full Monte Carlo CoREAS simulations, generally same features are seen in Fig. 8. Nevertheless, deviations from dominant geomagnetic contribution to the radio emission, as observed in Fig. 7, are associated to showers coming from the North and South directions. This is the consequence of the charge excess effect, with polarization radially towards the shower axis, which may be better observed at detectors placed at larger distance from the shower core [12], and moreover for showers with larger zenith angles.

4. CONCLUSIONS

All this analysis and even more can be found in the new updated version of the GUI application EAS Browser v2.0, which is available on Windows yet and can be freely downloaded [13]. The present work was aimed to highlight properties of air showers initiated by different type of primary cosmic ray at different energy and inclination angle, as well as to distinguish between the two emission mechanisms of the induced radio waves. It is obvious that the geomagnetic effect is the dominated mechanism in the radio emission process of air showers, while the partial contribution of the Askaryan effect it appears to be mainly associated to showers coming from North and South directions, varying in intensity with the zenith angle. Further attention will be put on analysis with observers placed at different distances from the shower core, for various shower incoming directions.

**Acknowledgements.** This work was supported by a grant of the Romanian National Authority for Scientific Research and Innovation, CNCS/CCCDI - UEFISCDI, project number PN-III-P1-1.2-PCCDI-2018-0839, within PNCDI III.

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