Astroparticle Physics 59 (2014) 29–38

Contents lists available at ScienceDirect

Astroparticle Physics

journal homepage: www.elsevier.com/locate/astropart

Radio pulses from ultra-high energy atmospheric showers as the superposition of Askaryan and geomagnetic mechanisms

Jaime Alvarez-Muñiz [a,*], Washington R. Carvalho Jr. [a], Harm Schoorlemmer [b], Enrique Zas [a]

[a] Departamento de Física de Partículas & Instituto Galego de Física de Altas Enerxías, Universidade de Santiago de Compostela, 15782 Santiago de Compostela, Spain
[b] University of Hawaii at Manoa, Department of Physics and Astronomy, Honolulu, HI 96822, USA

ARTICLE INFO

Article history:
Received 27 February 2014
Received in revised form 11 April 2014
Accepted 14 April 2014
Available online 26 April 2014

Keywords:
High energy cosmic rays
Extensive air showers
Askaryan radio emission

ABSTRACT

Radio emission in atmospheric showers is currently interpreted in terms of radiation due to the deviation of the charged particles in the magnetic field of the Earth and to the charge excess (Askaryan effect). Each of these mechanisms has a distinctive polarization. The complex signal patterns can be qualitatively explained as the interference (superposition) of the fields induced by each mechanism. In this work we explicitly and quantitatively test a simple phenomenological model based on this idea. The model is constructed by isolating each of the two components at the simulation level and by making use of approximate symmetries for each of the contributions separately. The results of the model are then checked against full ZHAireS Monte Carlo simulations of the electric field calculated from first principles. We show that the simple model describes radio emission at a few percent level in a wide range of shower-observer geometries and on a shower-by-shower basis. As a consequence, this approach provides a simple method to reduce the computing time needed to accurately predict the electric field of radio pulses emitted from air showers, with many practical applications in experimental situations of interest.

1. Introduction

In the last few years there has been a flurry of activity to explore the potential of the radio technique to study ultra high energy cosmic rays (UHECRs) [1]. The technique is attractive because it requires detectors which are relatively cheap and is not limited by a small duty cycle, unlike the fluorescence technique [2]. Several experimental initiatives such as AERA [3] and EASIER [4] in coincidence with the Pierre Auger Observatory [5], CODALEMA [6], LOPES [7], TREND [8], LOFAR [9] and Tunka-Rex [10], have been exploring emission from air showers mainly in the 30–80 MHz frequency range, studying the relation of the pulses to composition [11,12] and trying to understand the lateral distribution of the emission [13,14,3,9]. In addition the fortuitous detection of pulses from air showers with the ANITA balloon flown detector [15] has revealed that the pulses from these showers extend to the GHz regime, with more experimental evidence also obtained by the CROME experiment [16]. These studies are considered of primordial importance to explore the viability of the radio technique either to provide an alternative design of future air shower arrays covering areas in the range of 10,000 km^2 and above, or to use them as complementary detectors that could help to constrain the composition of the cosmic rays on a shower-by-shower basis.

On the phenomenological side there has also been a lot of progress. Calculations have been made based on the macroscopic treatment of the current densities that arise in these showers [17,18], and also on more detailed simulations that use the superposition principle to calculate the emission adding the contributions from single particle sub-tracks [19–22]. The results of these calculations, that reproduce pulses extending into the GHz regime as detected by ANITA [23], are now in reasonably good agreement [25] and they have been successfully tested against data [26,23,3,27,1]. As a result there is much more confidence in the calculations and it is believed that it is now possible to infer properties of the shower such as direction, energy and shower maximum using only measurements of the radio pulses in antennas scattered at ground level [28–31,1].

Radio emission in atmospheric showers is currently interpreted in terms of two dominant radiation mechanisms, namely the excess negative charge predicted by Askaryan in the 1960s (the Askaryan mechanism) [35], and that induced by the interactions of the particles with the magnetic field of the Earth that induces a net current perpendicular to the shower axis, the geomagnetic mechanism [36]. These two mechanisms induce distinctive electric

---

[*] Corresponding author. Tel.: +34 881813968.

E-mail addresses: jaime.alvarezmuniz@gmail.com (J. Alvarez-Muñiz), carvajr@gmail.com (W.R. Carvalho Jr.), harmscho@phys.hawaii.edu (H. Schoorlemmer), zas@fpaxp1.usc.es (E. Zas).

http://dx.doi.org/10.1016/j.astropartphys.2014.04.004
0927-6505/

field polarizations. Moreover the complex signal patterns observed at ground can be qualitatively explained as the interference (superposition) of the fields induced by each mechanism. In this work we quantitatively test this idea. For that purpose we have devised a phenomenological model that relies on standard approximate assumptions [17] and experimental observations of the characteristics of the radiation [33,34,6,27]. The model is constructed by isolating each of the two components at the simulation level and by making use of approximate symmetries for each of the contributions separately. The results of the model are subsequently checked against full ZHAireS Monte Carlo simulations of the electric field calculated from first principles. We show that the simple model describes radio emission at a few percent level in a wide range of shower-observer geometries and on a shower-by-shower basis.

The devised method reduces the calculation of the pattern at ground level to the pattern along a single line which can be sampled at a few points. This has a drastic effect on the required computing resources. This is of utmost importance since the study of the capabilities of detectors exploiting the radio technique as well as the reconstruction of cosmic ray shower parameters in detail requires full simulations of the shower and the radio pulses at a large variety of locations. Needless to say that a comprehensive parameterization of the patterns of the electric field at ground level would be most welcome as an alternative [32]. The approach presented here can be considered a step forward in this direction, since it can also simplify the creation of parameterizations.

This paper is organized as follows. In Section 2 we briefly review the main properties of radio emission in atmospheric cosmic ray showers. In Section 3 we describe the model to obtain the electric field induced by ultra-high energy cosmic ray showers in the atmosphere. In Section 4 we compare the electric field calculated with the model with that obtained in full Monte Carlo simulations. Finally, in Section 5 we conclude the paper and discuss future prospects.

2. Basics of radio emission in air showers

2.1. Radio emission mechanisms

Radio emission from showers initiated by cosmic rays in the atmosphere is discussed in terms of two mechanisms: the deflection of charges in the magnetic field of the Earth, the geomagnetic effect, and the development of an excess charge as the shower entrains electrons from the atmosphere into the shower front, the Askaryan mechanism. The different nature of the two mechanisms becomes apparent when we consider shower development without the magnetic field and only the Askaryan contribution exists.

The solution of Maxwell's equations in the transverse gauge relates the vector potential to the transverse current density, which in the limit of far observation distances is simply the projection of the current orthogonal to the direction of observation [37,38,40]. This is evident in a microscopic approach where currents are regarded as a sample of small particle sub-tracks of charge q moving at constant velocity $\vec{v}$, each of them contributing in proportion to $q\vec{v}_{\perp}$ [39,40], where $v_{\perp}$ refers to the projection of the sub-track into a plane perpendicular to the observation direction. The fact that the index of refraction is not constant in the atmosphere, that the particle tracks are not perfectly parallel to the shower axis and that the observation direction changes for each particle track complicates the picture but does not alter this fact.

The two mechanisms can be related to different components of the current density, perpendicular and parallel to the shower axis. The perpendicular component of the current is related to the geomagnetic mechanism and results from the Lorentz force induced by the geomagnetic field $\vec{B}$ that accelerates the charges in the direction $q\vec{v} \times \vec{B}$.[1] For the shower as a whole this current scales with $|\vec{B}| \sin\alpha$, with α the angle between $\vec{V}$ and $\vec{B}$, where $\vec{V} \simeq \langle\vec{v}\rangle$ is assumed to be parallel to shower axis. So the magnitude of the vector potential, hence the electric field, depends strongly on both the zenith, θ, and azimuth, ϕ, angles of the shower, which determine the value of α. Since electrons and positrons deviate in opposite directions they both contribute with the same sign to this component. The polarization to be expected for the vector potential is simply given by the projection of the $-\vec{V} \times \vec{B}$ direction onto a plane transverse to the observation direction. For observers positioned along the shower axis this coincides with $-\vec{V} \times \vec{B}$. This is the main mechanism for the radiation in extensive air showers.

The component of the current that is parallel to the shower axis is related to the Askaryan mechanism and arises because of the excess electrons in the shower front. The magnitude of the vector potential from this contribution is directly related to the excess charge as the shower develops in the atmosphere and the arrival direction of the shower has little effect on the magnitude of this excess. The vector potential is polarized along the projection of the shower axis onto the plane transverse to the observation direction, and has radial symmetry. It is thus zero along the shower axis and increases in proportion to sin β, where β is the angle between the shower axis and the observation direction [38,40]. The polarization of the vector potential has thus a strong radial component which increases as the observer deviates further away from shower axis.

2.2. Cherenkov like effects

The fact that the refractive index n of the atmosphere is greater than 1 is of utmost importance to understand the radio emission from air showers [41,18,21]. Since radio waves in air travel slightly slower than the shower particle front, shock wave effects similar to those observed in Cherenkov radiation play an important role in the time dependence of the electric field as seen by an observer on ground [18,21]. This in turn determines the amplitude and frequency spectrum of the observed radiation. In a simplified one-dimensional shower model [23], the emission from the point in the shower development that is seen by a particular observer at the Cherenkov angle arrives first and, more importantly, the emission from a region around it arrives with a much smaller delay than the rest of the shower. This is the result of the relation between observation, t, and retarded, t^*, times which is such that t has an absolute minimum with $dt/dt^* = 0$ in the Cherenkov direction [41,21]. The vector potential has an abrupt growth at this minimum t due to an effective "time compression" of the contributions from a relatively large region of the shower. This induces a strong and narrow pulse, coherent up to frequencies in the ~ GHz and with an enhanced power [15,16,23]. An observer thus becomes much more sensitive to the region of the shower seen at angles close to the Cherenkov angle. When the antenna lies in the Cherenkov direction with respect to the maximum of the shower $X_{\max}$, the detected electric fields are the largest, since more particles contribute to either of the mechanisms. These points of maximum radiation define a circular ring-like region on the plane perpendicular to the shower axis, or equivalently an elliptical region when projected onto the ground given by the intersection of a Cherenkov cone

---

[1] This has been referred to as a *transverse* current in the sense that it lies in a plane perpendicular to the shower axis.