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Macroscopic geo-magnetic radiation model; polarization effects and finite volume calculations

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ABSTRACT

An ultra-high-energy cosmic ray (UHECR) colliding with the Earth's atmosphere gives rise to an Extensive Air Shower (EAS). Due to different charge separation mechanisms within the thin shower front coherent electromagnetic radiation will be emitted within the radio frequency range. A small deviation of the index of refraction from unity will give rise to Cherenkov radiation up to distances of 100 m from the shower core and therefore has to be included in a complete description of the radio emission from an EAS. Interference between the different radiation mechanisms, in combination with different polarization behavior will reflect in a lateral distribution function (LDF) depending on the orientation of the observer and a non-trivial fall-off of the radio signal as function of distance to the shower core.

1. Introduction

Recent results to detect radio emission from UHECR induced particle cascades at the LOPES [1,2] and CODALEMA [3,4] experiments triggered plans to install a large array of radio antenna's at the Pierre Auger Observatory [5–7]. Both experiments clearly indicate that the main emission mechanism is induced by the deflection of charged particles in the Earth magnetic field. The emission process can be described in a microscopic approach as done in for example Ref. [8], where the field is calculated from the track of a single particle and a summation is done over all particles. A different approach is given by a macroscopic description where the coherent emission from induced macroscopic currents and charges in the shower front is calculated. This idea is investigated since the earliest days of radio detection from EAS [9–12]. Recently this approach is implemented using realistic shower profiles by the Macroscopic Geo-Magnetic Radiation (MGMR) [13–15] model. Recent results from comparison between the MGMR and REAS3 [16] simulations for the first time showed good agreement between two completely different models [17].

Due to the interest in detecting radio emission from cosmic ray induced particle cascades on a large scale at the Pierre Auger Observatory [5], it is of importance to understand the underlying emission mechanisms and their lateral behavior. In Ref. [15] the two most important emission mechanisms, geomagnetic radiation and radiation due to a net negative charge-excess in the shower front also known as the Askaryan effect, are discussed. It follows that the LDF depends strongly on the geometry considered and one has to take into account the observer angle dependency. In Section 2 we will give a short review of the MGMR model and the different radio emission mechanisms. Interference effects and polarization patterns for the different mechanisms will be discussed in Section 3. The consequences of these effects for the LDF will be discussed in Section 4. Finally the effect due to the small deviation of the index of refraction from unity leading to Cherenkov radiation will be discussed in Section 5.

2. The model

The MGMR model describes the emission due to the variation of a net macroscopic current in the shower front. This current, as follows from Monte-Carlo simulations, can be described using three macroscopic distributions. The total number of particles in the thin shower front at a fixed negative emission time $(t'<0), f_t(t')$. The longitudinal distribution of particles in the shower front, $f_p(h)$, where h is the distance in meters behind the imaginary shower front traveling with the speed of light toward the surface of the Earth, and the lateral distribution of particles within the shower front which is neglected at the moment. It follows that the pulse shape and height contain direct information about these macroscopic distributions [18].

The shower front will be located at a height $z=-\beta t'$, defined in such a way that $t'=0$ when the shower hits the surface of the Earth. Hence the total number of particles corresponding to the negative emission time t' at a height $z=-\beta t'+h$ is given by

$$N(z,t') = N_e f_t(t') f_p(h) \quad (1)$$

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where N_e is the total number of particles in the shower at the shower maximum. The induced current in the pancake is now given by

$$j^{\mu}(x,y,z,t') = v^{\mu} q e N(z,t') \delta(x)\delta(y) \tag{2}$$

where q is the charge of the particles considered, v^{μ} the four-velocity, and the $\delta(x)\delta(y)$ term takes care of the lateral distribution of the particles in the shower front, hence all particles are projected along the shower axis.

The electric field is now obtained through the Liénard Wiechert potentials from classical electrodynamics [19],

$$A^{\mu}(\vec{x},t) = \left.\frac{j^{\mu}(\vec{x},t')}{\mathcal{D}}\right|_{t'=t_r} \tag{3}$$

to be evaluated at the retarded time $t' = t_r$ given by

$$ct_r = \frac{ct - n^2 \beta_s h - n\mathcal{D}}{(1-n^2\beta_s^2)}. \tag{4}$$

Here n is the index of refraction of air, t is the observer time, and $\mathcal{D}$ is the retarded distance given by,

$$\mathcal{D} = \sqrt{(-c\beta_s t + h)^2 + (1-n^2\beta_s^2)d^2}. \tag{5}$$

The electric field is now obtained through the standard relation,

$$\vec{E}(\vec{x},t) = -\frac{d}{d\vec{x}} A^0(\vec{x},t) - \frac{d}{d(ct)} \vec{A}(\vec{x},t). \tag{6}$$

3. Polarization and interference

In Refs. [13,14] several different emission mechanisms are discussed. We will focus on the three strongest contributions. The geomagnetic emission mechanism due to the deflection of electrons and positrons in the Earth magnetic field, gives rise to a net current in the direction of the Lorentz force acting on these particles. A secondary moving dipole contribution due to the geomagnetic charge separation inside the shower front, and the emission due to a net charge-excess in the shower, also known as the Askaryan effect [20].

We study the ground polarization pattern for a perpendicular incoming air shower with the magnetic field pointing to the North. Since for the geomagnetic contribution an equal amount of electrons and positrons is assumed, only the vector potential in the direction of the induced drift velocity survives since the electrons and positrons are deflected in opposite directions in the Earth magnetic field. From Eq. (6) it follows immediately that the signal is, independent of observer position, fully polarized in the $\hat{n} = -\vec{e}_{\beta} \times \vec{e}_B$ direction, where e_{β} is the unit vector pointing along the shower axis, and e_B the unit magnetic field vector Fig. 1 (top).

The zeroth component due to the net charge-excess in the shower front gives rise to a radial polarization pattern shown in Fig. 1 (bottom) [14,21]. The xy-polarization pattern, projected on the ground plane, for the moving dipole contribution is given by a typical dipole pattern. A direct consequence of the different polarization patterns is different interference behavior as function of observer position. In the case that the geomagnetic and moving dipole polarization are pointing to the East, an observer placed West from the shower core will see constructive interference between the charge-excess and geomagnetic component in the East–West polarization and see nothing in the North–South polarization. When the observer is placed to the North of the shower core, the geomagnetic field will still be seen in the East–West polarization, whereas the charge-excess field is pointing in the North–South direction and no interference will take place. An observer placed to the East of the shower core will again see no field in the North–South polarization, nevertheless the charge-excess and geomagnetic components on this side of the shower core will interfere destructively. These interference effects as function of observer position can give a great tool to disentangle and study the different emission mechanisms [22].

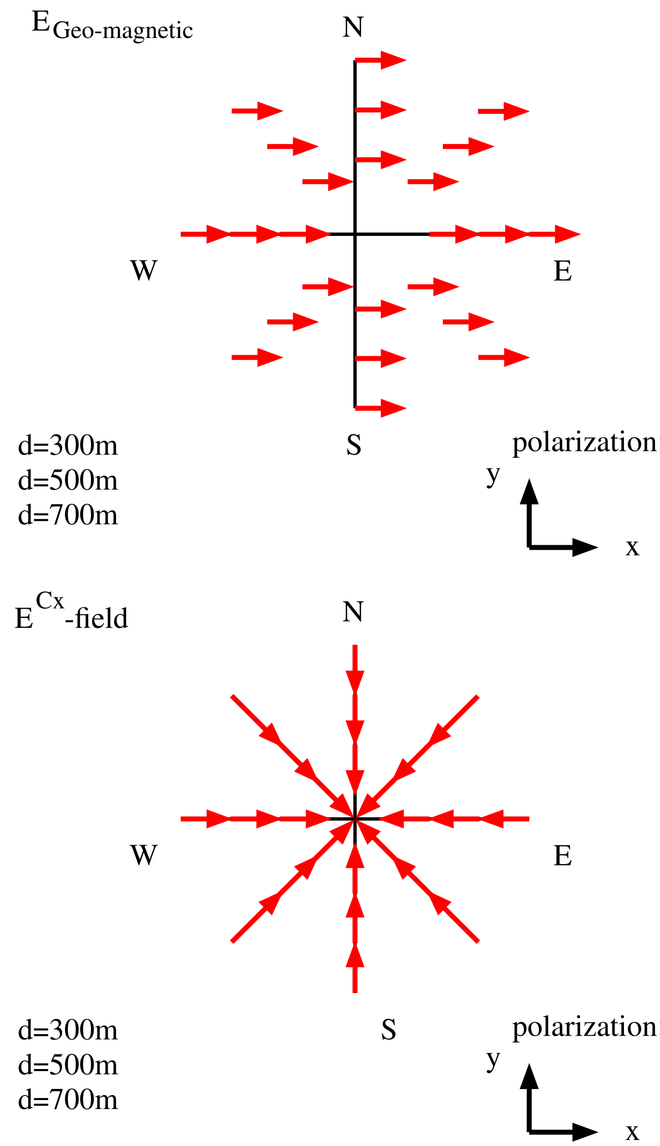

Fig. 1. The polarization in the xy-plane seen by an observer at different observer positions w.r.t. the impact point of the shower for the geomagnetic contribution (top), and the charge-excess contribution (bottom).

4. Radial dependence of the radio signal

As discussed in the previous section, the interference between different contributions is strongly observer position dependent. As a direct consequence one has to be extremely careful in determining an LDF [23]. For different observer positions constructive or destructive interference can take place and the field strength will, depending on the geometry, have strong fluctuations.

In Fig. 2 the LDF for the three different contributions is shown for the maximum of the unfiltered electric field strength. It can be seen that the LDF's for the geomagnetic contribution and the dipole contribution follow each other, whereas the LDF for the charge-excess contribution is less steep and at distances larger than