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Simulation Cherenkov and Synchrotron Radio Emission in EAS

R. Engel[a], N.N. Kalmykov[b] and A.A. Konstantinov[b]
(a) Forschungszentrum Karlsruhe, Institut fuer Kernphysik, Postfach 3640, D-76021 Karlsruhe, Germany
(b) Skobeltsyn Institute of Nuclear Physics, Moscow State University, Leninskie Gory 1, 119992, Moscow, Russia
Presenter: R. Engel (Ralph.Engel@ik.fzk.de), ger-engel-R-abs3-he11-poster

Cherenkov and geosynchrotron radiation are considered as two fundamental mechanisms of the radio emission generated by extensive air showers (EAS). The code EGSnrc is used for Monte-Carlo simulations of the individual shower development. Calculations of the radial dependence and frequency spectrum of the emitted radiation are performed for the LOPES experiment frequency range.

1. Introduction

Coherent radio emission generated by extensive air showers was theoretically predicted by Askaryan in 1961 [1] and experimentally discovered by Jelly et al. in 1965 at a frequency of 44 MHz [2]. Over a period of time this phenomenon has been considered as an interesting alternative to traditional methods of detection of high-energy cosmic rays with energy greater than 10^{17} eV. In the 1960th and 1970th the experimental and theoretical efforts in this direction had no actual success [3]. Modern experiments, such as CODALEMA [4] and LOPES [5], aimed at EAS radio emission studies use modern, improved instruments and thus can hope for the final success. But there are still many questions concerning the quantitative radio emission theory.

Several mechanisms of radio emission generation in air have been identified after the pioneering work of Askaryan where the coherent Cherenkov radiation of the charge-excess was put forward [1]. This radiation is very strong for showers developing in dense media [6]. In the case of EAS there is also an alternative radiation due to the acceleration of charged shower particles in the Earth's magnetic field. It is called geosynchrotron mechanism and has been recently investigated in detail [7]. However we still have no sufficiently clear understanding what interrelation exists between these two essential mechanisms. So, one needs to perform accurate radio emission calculations for these mechanisms within the framework of a unified approach. In our work we present a model in which Cherenkov and geosynchrotron radiation are combined. In a sense, our work is complementary to [7] where only the geosynchrotron radiation was considered.

2. Calculations

To calculate the radio emission of air showers an EGSnrc-based [8] program code has been developed. For reproduction of the Earth's atmosphere we have taken 200 strata of air, with density and optical properties varying from stratum to stratum according to the atmospheric profile. The declination and strength of the Earth's magnetic field [9] correspond to those for Karlsruhe, where the LOPES experiment is being performed. Radio emission characteristics (radial dependence, frequency spectrum, polarization and some others) are calculated taking into account contributions from each charged particle.

There are two different radiation mechanisms adopted in the model and the separation of them is realized as follows. If a charged particle is moving in the magnetic field characterized by the field strength $\boldsymbol{B}$ and the refractive index is equal to n, we may present the electric field $\boldsymbol{E}$ as the sum of two parts with the following properties

$$\boldsymbol{E} = \boldsymbol{E}_{(1)} + \boldsymbol{E}_{(2)},$$

where $\boldsymbol{E}_{(1)} \rightarrow \boldsymbol{0}$, when $\boldsymbol{B} \rightarrow \boldsymbol{0}$, and $\boldsymbol{E}_{(2)} \rightarrow \boldsymbol{0}$, when $n \rightarrow 1$. We accept that $\boldsymbol{E}_{(1)}$ is the electric field due to the Earth's magnetic field (*geosynchrotron radiation*) and $\boldsymbol{E}_{(2)}$ is the electric field due to medium (air) properties (*Cherenkov radiation*).

3. Simulation results

Vertical showers were simulated for primary photons with the energies 1 and 10 TeV and for energy thresholds of 100 keV and 1 MeV. The primary particle is injected at 30 km above the ground level. The lateral distributions of radio emission were calculated simultaneously at several frequencies: 10, 30 and 100 MHz. In total 50 ground-level observation points were uniformly distributed over a straight line from the shower axis to the direction of the geographic north in the range of distances up to 500 m.

The mean longitudinal profile of showers with 1 TeV primary photon energy and 1 MeV threshold energy is presented on Figure 1. Such showers have the negative charge excess (ε) of about 20% in the maximum. It should be stressed that electrons and positrons emit Cherenkov radiation if their energy exceeds the Cherenkov threshold (that is equal to 21 MeV at sea level) and thus only ≈ 1/3 of the above-mentioned excess particles give a contribution to the observed electric field. This is in contrast to the situation in ice where, due to a rather large refractive index, almost all excess particles emit Cherenkov radiation.

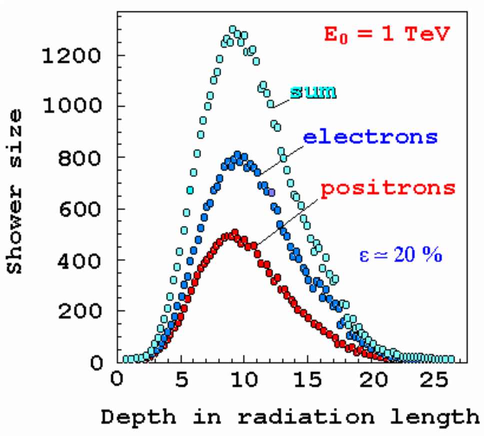

Figure 1. Number of shower particles as a function of depth (E_{thr} = 1 MeV, averaged over 20 showers).

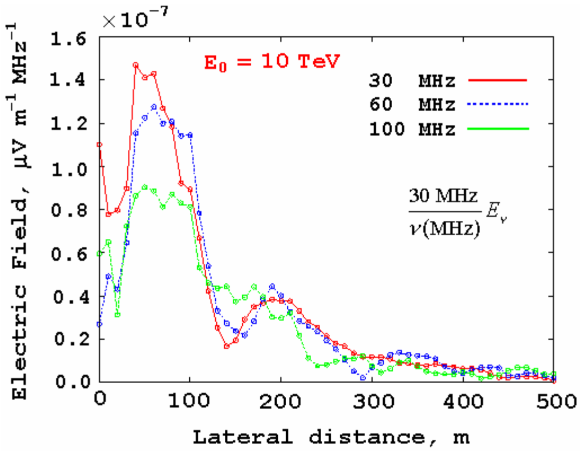

Figure 2. Lateral distribution of Cherenkov radio emission at different frequencies (E_{thr} = 100 keV, 5 showers).

Figure 2 shows the lateral distribution of the electric field produced by Cherenkov radiation of shower particles. The primary energy is 10 TeV and the electric field is normalized at the frequency 10 MHz. We associate this radiation with Askaryan's mechanism (radiation of the negative charge excess). This idea was confirmed by direct calculations: when the excess is zero then we have a decrease of the field by two to three orders of magnitude (depending on the considered frequency). It is also interesting to note that the Cherenkov radiation demonstrates a diffraction pattern.

The full pattern of the radio emission lateral distribution is shown in Figure 3 for 10 TeV-showers. Plotted are the Cherenkov, geosynchrotron and total (the sum of Cherenkov and geosynchrotron contributions) radio emission at 30 and 100 MHz. We see that there exists practically full domination of the geosynchrotron radiation in the low frequency part of the radio emission spectrum at all distances. But it is not so for higher frequencies and especially at the main Cherenkov peak.

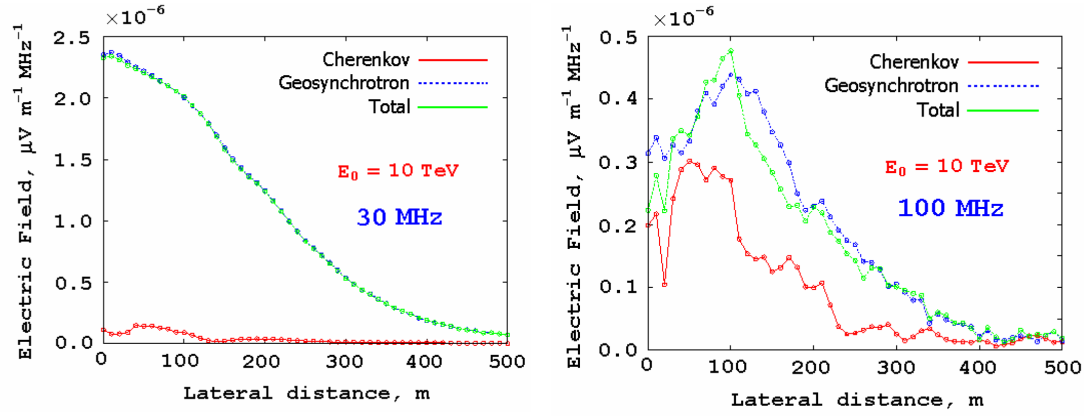

Figure 3. Lateral distribution of geosynchrotron, Cherenkov and total radio emission at different frequencies (E_{thr} = 100 keV, averaged over 5 showers).

It seems that we can interpret this behavior as due to the difference in spectral properties of the two types of radiation. This is confirmed by Figure 4 where the spectral distribution of the radio emission at 100 and 300 m from the shower axis of 1 TeV-showers are shown. We see (picture for 100 m) that the coherent regime for the Cherenkov emission is maintained up to higher frequencies than in the case of the geosynchrotron emission. It seems that the main reason of this situation is that the effective dimension of the radiation region is smaller for the Cherenkov emission than for the geosynchrotron emission due to the large Cherenkov threshold energy. The situation is similar at larger distances from shower axis (results are given at 300 m).

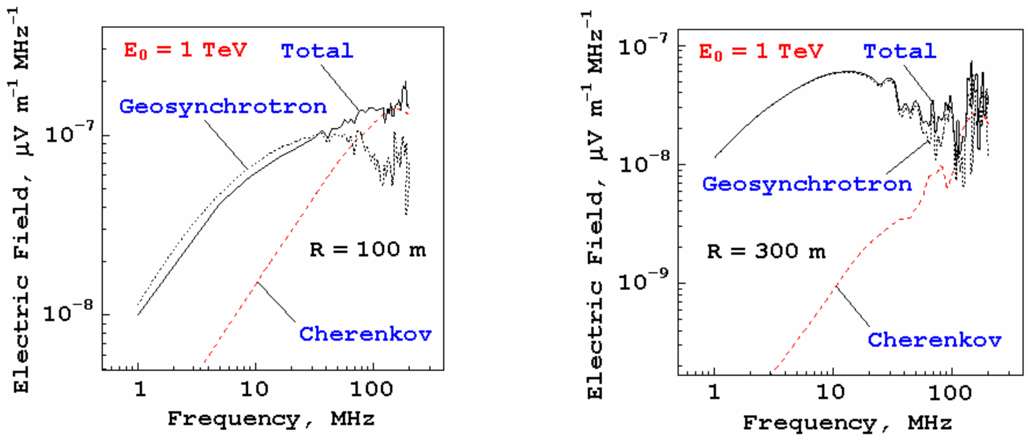

Figure 4. Spectral distribution of geosynchrotron, Cherenkov and total radio emission at different distances from shower axis (E_{thr} = 1 MeV, averaged over 5 showers).

4. Conclusions

Realistic air shower and radio signal simulations for primary energies 1÷10 TeV have been performed. The calculations show that there is no full domination of one of the two radiation mechanisms in the Earth's atmosphere. It seems that an appropriate radio emission theory needs to take into account the Cherenkov radiation as well as the geosynchrotron mechanism.

The contribution of the Cherenkov radiation to the total field is not identical at different distances from shower axis. At small distances, including the main peak, the role of the Cherenkov component grows with the increase of the observation frequency due to violation of the coherence condition for the geosynchrotron radio emission whereas it is conserved for the Cherenkov radiation. We also observe the same situation at larger distances from shower axis. However the flow of the geosynchrotron radio emission falls with distance more slowly than for the Cherenkov emission and thus the amplitude of the Cherenkov radiation at these distances is much smaller.

The amplitude of the geosynchrotron mechanism essentially depends on the configuration of the system "shower axis - magnetic field" and there is a need to simulate showers with different arrival directions relative to the local magnetic field. In parallel one certainly needs to push up the primary energy and statistics of the simulations to attain better understanding of radiation processes in air.

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