ISSN 0027-1349, Moscow University Physics Bulletin, 2007, Vol. 62, No. 4, pp. 266–267. © Allerton Press, Inc., 2007.
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Simulations of Radio Emission from Ultrahigh-Energy Extensive Air Showers

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Abstract—The radio emission from extensive air showers with energies up to 10^{17} eV has been calculated. The calculated lateral distribution of the radio emission is in good agreement with the LOPES-10 experimental data.

DOI: 10.3103/S0027134907040145

INTRODUCTION

Within the KASCADE array [1], the LOPES experiment [2] aimed at studying the radio emission from extensive air showers (EASs) and developing a method for detecting cosmic rays with energies above 10^{17} eV [3] came into operation in 2004. LOPES is designed to perform initial calibration of the radio technique and to test a quantitative model for EAS radio emission.

In this paper, we present the results of our simulations of the lateral distribution of radio emission from a vertical EAS with energy 10^{17} eV. Our calculations are compared with the LOPES-10 (10 is the number of radio antennas in the array) experimental data at distances up to 300 m from the shower axis at frequencies of 40 and 80 MHz.

SIMULATIONS

We calculated the EAS radio emission with a specially developed code that summed the emissions from individual shower particles. The EGSnrc code [4] was used to simulate the EAS electron–photon component. The density and optical properties of the Earth's atmosphere were changed discretely at steps of 9.5 g cm^{-2}. The magnitude and direction of the geomagnetic field corresponded to those at the site of the LOPES experiment [2].

In the Fraunhofer approximation, the Fourier component of the electric field at frequency $\omega = 2\pi\nu$ produced by an electron e that moves rectilinearly and uniformly with velocity $\mathbf{u}$ in the time interval from t_0 to $t_0 + \Delta t$ is

$$\mathbf{E}_\omega(x_a) = \frac{e}{8\pi^2\varepsilon_0 c}\frac{e^{ikR}}{R}e^{i\omega(t_0 - n\mathbf{e}_R\cdot\boldsymbol{\xi}_0/c)} \times\left(\frac{e^{i\omega\Delta t(1 - n\mathbf{e}_R\cdot\boldsymbol{\beta})} - 1}{1 - n\mathbf{e}_R\boldsymbol{\beta}}\right)\beta_\perp. \qquad (1)$$

Here, ε_0 and c are the dielectric constant and the speed of light in a vacuum, respectively, $k = n\omega/c$, n is the refractive index of the air, R is the distance from the electron to the radio signal reception point x_α, $\mathbf{e}_R = \mathbf{R}/R$, $\boldsymbol{\xi}_0$ is the radius vector of the electron at time t_0, $\boldsymbol{\beta} = \mathbf{u}/c$, and $\boldsymbol{\beta}_\perp = -[\mathbf{e}_R, [\mathbf{e}_R, \boldsymbol{\beta}]$. The emission was calculated using Eq. (1) for all particles above the 100-keV simulation threshold.

At present, the direct Monte Carlo simulations of air showers are limited to an energy of 10^{15} eV. A traditional means of raising the energy limit is the "thinning" of air showers suggested in [5]. Unfortunately, this method produces a gain of no more than a factor of 10 for the calculation of EAS radio emission, since the particles of precise low energies (much lower than the critical one of 81 MeV) play a large role in the radio wavelength range. It has become possible to simulate the radio emission from a single vertical air shower formed by photon with energy $E_0 = 10^{17}$ eV through the use of a cluster of computers (KASCADE, Institut fuer Kernphysik, Karlsruhe). The air shower was thinned for particles with energies below 20 GeV, which allowed the radio field to be calculated at distances up to 300 m. The lateral distribution of the radio emission was obtained in four directions from the shower axis at frequencies of 40 and 80 MHz. When 50 (2 GHz) processors operated simultaneously, it took one month for the entire calculation.

RESULTS

The radio emission was calculated for the air shower corresponding to the mean cascade curve. The longitudinal profile of this air shower is presented in Fig. 1.

The theoretical strength of the radio field is compared with the LOPES-10 data in Fig. 2, where the calculated field was averaged over the northern, southern, western, and eastern directions of observation. The experimental dependence of the EAS radio signal amplitude was constructed from a sample of 372 events

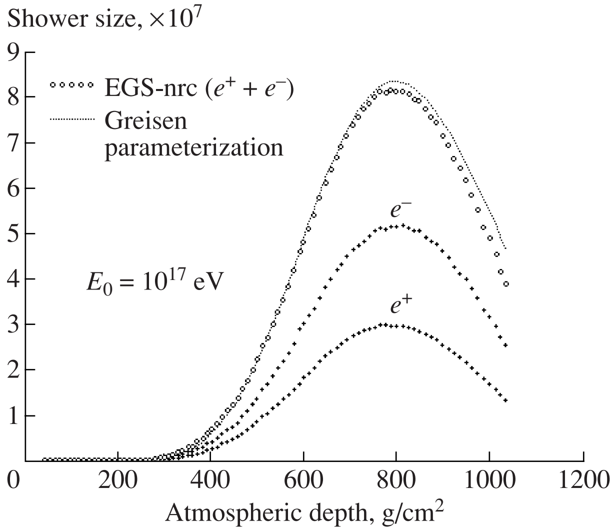

Fig. 1. Longitudinal profile for a vertical air shower with energy $E_0 = 10^{17}$ eV: e^- is the number of electrons, e^+ is the number of positrons, and $e^- + e^+$ is their sum.

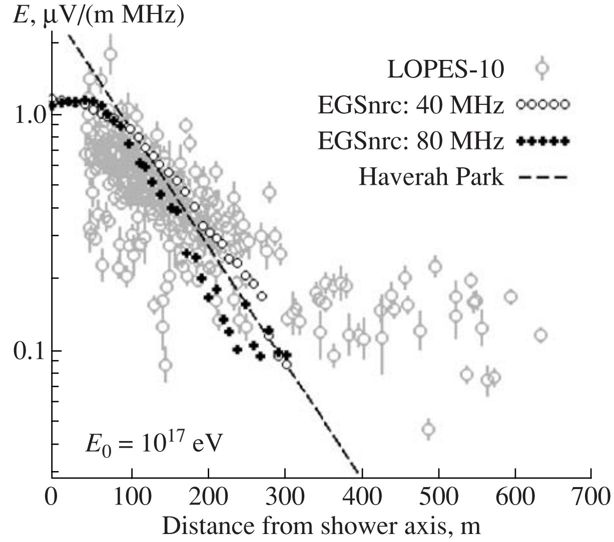

Fig. 2. Lateral distribution of radio emission. Our (EGS-nrc) data, the LOPES-10 experimental data [6], and the fit to the Haverah Park data [7] are compared.

accumulated in 6 months of LOPES-10 operation [6]. The sample is represented by EASs with energies from 5×10^{16} to 6×10^{17} eV. As we see, our calculations accurately describe the behavior of the experimental data points. A simple extrapolation of the calculated curves to distances >300 m at a given thinning level (20 GeV) is not possible.

The same figure shows a fit to the Haverah Park experimental data [7]. This fit obtained for EASs with energies from 10^{17} to 10^{18} eV and with arrival angles <35° is valid in the range of distances up to 300 m (at 55 MHz). The Haverah Park data closely correspond to the calculated radio field at distances 100–300 m. The difference at $R < 100$ m stems from the fact that a dependence of the form $f(R) \sim \exp(-R/(110\text{ m}))$ [7] poorly describes the data in this range of distances [7, 8].

CONCLUSIONS

The actual boundary of the direct Monte Carlo simulations of radio emission (10^{15}–10^{16} eV) is still far from the range of extremely high energies (10^{20} eV or higher). The primary particle energy can be increased in principle only within the framework of a macroscopic approach that considers EAS in terms of the electric moments and currents that it acquires through the accumulation of an excess of electrons and the systematic separation of electrons and positrons in the geomagnetic field. In essence, only these two (purely collective) effects in the development of air showers produce their radio emission [3]. Therefore, it is natural to pass from simulating the trajectories of individual particles to calculating the excess of electrons and the geomagnetic EAS polarization as functions of the depth.

ACKNOWLEDGMENTS

We are grateful to Dr. W. Apel for his advice in working on the KASCADE computer cluster. This study was supported by INTAS (grant no. 05-109-5459).

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