Effects of atmospheric electric fields on radio emission from air showers

T. N. G. Trinh[1], O. Scholten[1], A. M. van den Berg[1], S. Buitink[2],
U. Ebert[3], C. Rutjes[3], C. Köhn[3]

[1] *KVI – Center of Advanced Radiation Technology, University of Groningen, The Netherlands*
[2] *Department of Astrophysics, Radboud University of Nijmegen, The Netherlands*
[3] *CWI, Amsterdam Science Park, The Netherlands*

We study the effects of atmospheric electric fields on air showers and their radio emission. We find that an electric field of the order of 100kV/m significantly changes the number of electrons and positrons in showers. In fair-weather conditions, the dominant strength of radio emission from cosmic ray air showers is driven by the geomagnetic field. However, when showers pass through strong electric fields, the charge excess radiation, which under fair-weather conditions gives only a contribution of secondary importance to the radiated intensity, may be strongly enhanced. Studying the effects of electric fields on showers and their radio emission will thus contribute to a better understanding not only of the shower mechanism but also of the atmospheric electric field.

1. Introduction

When a high-energy cosmic ray impinges on the atmosphere of the earth a particle cascade is produced with copious amounts of electrons and positrons. These particles are concentrated at the front of the shower, forming a so-called pancake that moves to the ground with the speed of light. These electrons and positrons are deflected in opposite directions by the magnetic field of the Earth which results in a macroscopic electric current which will emit radio waves. In addition, due to the knock-out of electrons from air molecules, there is an excess of electrons. This charge excess also contributes to emission of radio waves but is, in fair weather conditions, of secondary importance as compared to the geomagnetic radiation. The two can be distinguished on the basis of the polarization of the emission as well as the structure of the footprint [1, 2].

When showers pass through strong electric fields, such as may be found in thunderstorm conditions, the amount of charge excess in the shower is strongly affected [3]. This will result in large changes in the footprint of the emitted radio emission. The study and understanding of the effects of atmospheric electric fields is thus of importance for a correct interpretation of the radio footprint in terms of shower parameters. Alternatively the radio footprint from cosmic rays may be used to learn about atmospheric electric fields. In the present work these effects are investigated using numerical simulations.

2. Radio emissions simulation

The CORSIKA and CoREAS [4, 5] codes are used for performing the numerical simulations. The CORSIKA code performs a Monte Carlo simulation of the air shower development. The radio emission is calculated in CoREAS by tracing individual particles.

3. Effects of the atmospheric electric field

3.1. Effects on shower charges

Fig.1 shows simulation results for a vertical shower generated by a proton with an energy of 10^{17} eV with and without an electric field. The electric field points vertically upward and it thus accelerates electrons and decelerates positrons in the shower. In the present calculation the magnitude is taken as 100 kV/m from the ground up to 10 km for simplicity. A more realistic electric field that depends on the air density will be studied in the future.

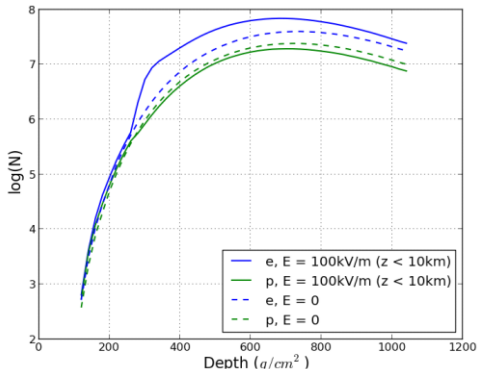


Fig 1: Number of electrons and positrons as a function of atmospheric depth

The numbers of electrons and positrons (on a logarithmic scale) are plotted as a function of depth. At the point where the electric field is switched on, the number of electrons grows strongly while the

number of positrons decreases lightly. This figure also shows that the net charge remains almost the same in the region where the electric field is present.

In addition to causing a change in the number of charged particles the presence of an electric field affects their energy distribution. When the electric field is applied, the shower electrons gain energy while the positrons lose energy. On the other hand, the charged particles lose their energy through the radiation process. The change in energy U of a particle with charge q per unit of atmospheric depth X is [6]:

$$dU = -\frac{U}{X_0}dX + \frac{qEz_0}{X}dX \qquad (1)$$

where the radiation length X_0 is 36.7 g/cm^2 and $z_0 \approx 8.4$ km. The particle obtains an equilibrium energy when $dU = 0$ or

$$U_0 = \frac{qEz_0X_0}{X} \qquad (2)$$

Particles which have energies below U_0 will be accelerated, while above this energy the energy loss due to radiation is dominant.

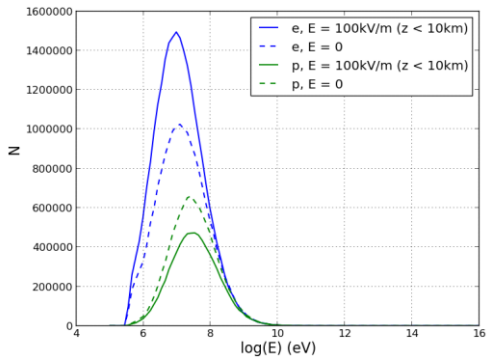
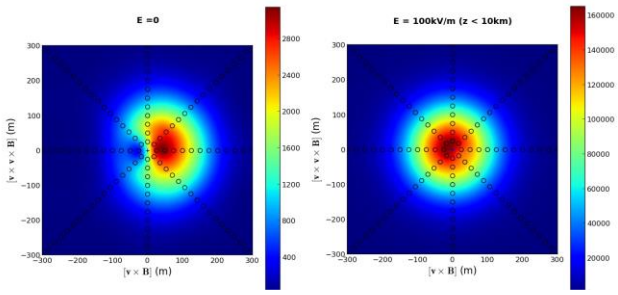


Fig 2: Kinetic energy distribution on the ground with and without electric field

Fig.2 shows the kinetic energy distribution of electrons and positrons on the ground in the presence of an electric field (solid lines) and without (dash lines). At very large energies, there is no significant effect of the electric field as follows from the discussion above. At lower energy regions, electrons are accelerated and gain energy from the field. These accelerated electrons generate more charged particles thus causing a strong enhancement in number. In contrast, positrons lose energy due to radiation as well as the electric field, and hence the number of positrons on the ground decreases.

3.2. Effects on radio pattern

Fig.3a shows the radio pattern of an inclined shower with a zenith angle of 25 degrees in the absence of an electric field. The core of the shower is in the center and the small circles mark the positions of antennas put in CoREAS. An interpolation is done to get signal strength at other positions. This figure shows that the maximum value of signal lies on $v \times B$ axis where the geomagnetic and charge excess radiations are added constructively. The minimum lies on the opposite direction when these components are subtracted.



(a) (b)

Fig 3: Radio pattern with and without electric field

When the electric field is switched on, since the net charge rises significantly, the contribution of charge excess in the radio pattern increases considerably. However, the total number of charges does not change much resulting an almost unchanged geomagnetic contribution. Fig.3b shows the radio pattern of the same shower in the presence of the electric field. There is a clear circle in the pattern visible which presents the charge excess radiation. The strength of signals also increases dramatically.

4. Conclusion and outlook

A 100 kV/m field has a significant effect on the number of charge particles in the shower, their energy distribution and the radio pattern. We are presently investigating the quantitative relation between the electric field and the charge excess as this is essential for the change in the radio pattern.

5. References

[1] K. Werner and O. Scholten, Astropart. Phys. 29, 393-411 (2008).

[2] O. Scholten, K.D. de Vries, K. Werner, EPJ Web of Conf. 53, 08005 (2013).

[3] S. Buitink, T. Huege, H. Falcke, and J. Kuijpers, Astropart. Physics 33, 296306 (2010).

[4] D. Heck et al., Report FZKA 6019 (1998).

[5] CoREAS v0.9 T. Huege et al. AIPC 1535, 128 (2013)

[6] S. Buitink, T. Huege, H. Falcke, D. Heck, J. Kuijpers arXiv:0910.5268.