Effects of atmospheric electric fields on the evolution and radio emission of extensive air showers

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Abstract. **Atmospheric electric fields can have an influence on the development of extensive air showers and the radio emission they emit. For the radio detection of air showers it is of vital importance to know the magnitude of this effects and the weather conditions under which it becomes significant.**

The physical mechanism that produces the amplified radio pulses is investigated and simulated in two steps. The first step is simulation of the development of air showers in the presence of a background electric field with an upgraded version of CORSIKA. The second step is simulation of the radio emission of air showers in electric fields. The radio simulation code REAS2 is extended with a routine describing the trajectories of charges in an electromagnetic field.

***Keywords*: air showers - radio emission - atmospheric electric fields**

I. INTRODUCTION

The electrons and positrons in extensive air showers are separated in the geomagnetic field, giving rise to a detectable radio signal [1]. This radiation can be described in terms of geosynchrotron emission [2] and can be simulated with the Monte Carlo code REAS2 [3][4], which calculates the radio emission of particles from air showers produced with CORSIKA [5]. Alternatively, the radio signals can be analytically derived in terms of a time dependent transverse current [6][7].

Already in the 1970s it was discovered that the radio pulse of an air shower may be larger than anticipated when strong electric fields are present in the atmosphere [8]. Using LOPES data recorded during various weather types it was shown that an amplification of the radio pulse can occur during thunderstorm conditions [9]. In another study it was shown that the arrival direction reconstructed with radio data and particle detector data can differ by a few degrees during thunderstorms [10].

In this work, we simulate the influence of a background electric field on the development of air showers and their radio emission with CORSIKA and REAS2.

In fair weather, i.e. atmospheric conditions in which electrified clouds are absent, there is a downward electric field present with a field strength of $\sim 100\,\mathrm{Vm}^{-1}$ at ground level. The field strength decreases rapidly with altitude and has values below 10 Vm^{-1} at altitudes of a few hunderd meter and higher. Most clouds can typically gain field strengths of a few hundred Vm^{-1}. Nimbostratus clouds, which have a typical thickness of more than 2000 m can have fields of the order of $10\,\mathrm{kVm}^{-1}$. The largest electric fields are found inside thunderstorms, where locally field strengths can reach values up to $100\,\mathrm{kVm}^{-1}$. In most clouds this field is directed vertically, but thunderclouds contain complex charge distributions and can have local fields in any direction. Thunderclouds can have a vertical extent of $\sim$ 10 km [11]. In this work, we use the convention that a positive field points downwards and accelerates the positrons. In the all simulations presented a homogeneous background field is used.

The electric field can influence the radio signal of air showers in several ways. First, the spatial and energy distribution of the electrons and positrons can be altered. Depending on the electric field direction, the electrons are accelerated or slowed down, while the positrons experience the opposite effect. The direction of the particles could also change. Second, the emission mechanism itself is different because the acceleration of particles by the transverse component of the electric field is added to the transverse acceleration due to the magnetic field.

Another issue related to the electric field is the suggestion that air showers of sufficient energy can start an avalanche of runaway electrons in thunderstorm electric fields. Ionization electrons that are produced in collisions of shower particles with air molecules are accelerated in the thunderstorm electric field and can, under the right conditions, gain enough energy to ionize further molecules, an effect described by Gurevich et al. [12]. In thunderstorm research the field strength that can support such avalanches is known as the breakeven field, described in Marshall et al. [13]. In their work, the authors present thunderstorm measurements which show that lightning often occurs when the thunderstorm field exceeds the breakeven field, suggesting that runaway electron breakdown plays a role in lightning initiation. By providing seed electrons for avalanches, air showers from cosmic rays may play an important role in thunderstorm dynamics. The runaway breakdown process can also explain the observation of X-ray and gamma ray emission coming from thunderstorm clouds [14] in terms of bremsstrahlung emitted by the runaway breakdown electrons [15].

II. CORSIKA RESULTS

Electromagnetic interactions are simulated by the standard CORSIKA (version 6.720) routines to treat electromagnetic particles. These routines are taylor-made versions of the EGS4-code [16] adapted to the barometric atmosphere with a density decreasing exponentially with increasing altitude. All possible interactions are considered and a proper treatment of ionization energy loss and multiple scattering is performed.

By including some suitable extra statements into the transport routine ELECTR for $e^{+/-}$ particles the effects of an external electrical field are taken into account which causes an acceleration (energy gain rsp. loss) for particles moving parallel to the field and a deflection for those moving perpendicular to the field. A suitable limitation of the transport step length guarantees small changements of the particle movements to neglect higher order effects on the particle traces. By these means the energy gain/loss in the electrical field and the ionization energy loss can be treated independently for each transport step.

In our simulations we use the high-energy hadronic interaction model QGSJET-II [17] and for low-energy hadronic interactions we use UrQMD 1.3cr [18]. We use the “thinning” option with thinning at 10^{-7} level and optimized weight limitation [19] to keep the computing times below a tolerable level.

When simulating showers with the same primary particle but different random seeds fluctuations will occur from shower to shower. Most importantly the altitude of the first interaction varies, but also the location of the shower maximum, for example, is dependent on number of particles that are produced in the first interaction, and the energy distribution of these particles. Because we are investigating the effect of a background electric field on the shower development we want to suppress the shower-to-shower fluctuations. Therefore, we use CONEX [20] to make 100 proton shower simulations of the same primary energy and direction. From these 100 simulations we select a shower with a large number of secondary particles in the first interaction and a fairly typical longitudinal shower profile. CONEX produces a file that lists all secondary particles after the first interaction and their momenta, which can be used as an input stack for CORSIKA using the STACKIN option. With a CONEX stack of particles created at the first interaction instead of one primary particle as input, different random seeds will produce much smaller variations. For each shower configuration we have selected a CONEX input stack and used this to produce ten showers with different random seeds. In the following plots of shower evolution we plot the mean value of these ten showers and one sigma error bars. Because the fluctuations between simulations are very small with this approach, we are more senstitive to changes that are introduced by the background electric field.

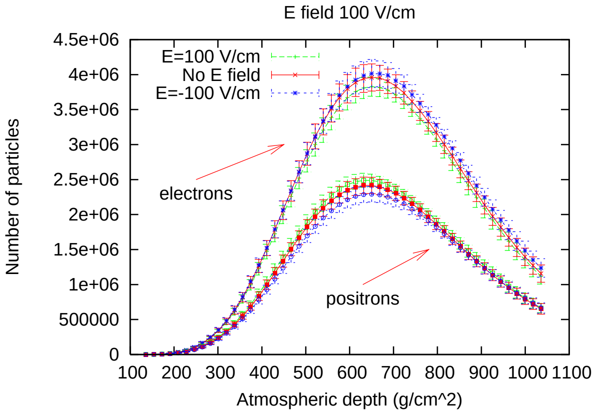

Fig. 1: Number of electrons and positrons as a function of atmospheric depth for a vertical 10^{16} eV proton shower. The different colors correspond to different background electric fields. In a field of ±100 V/cm, the deviations are within 1σ errors.

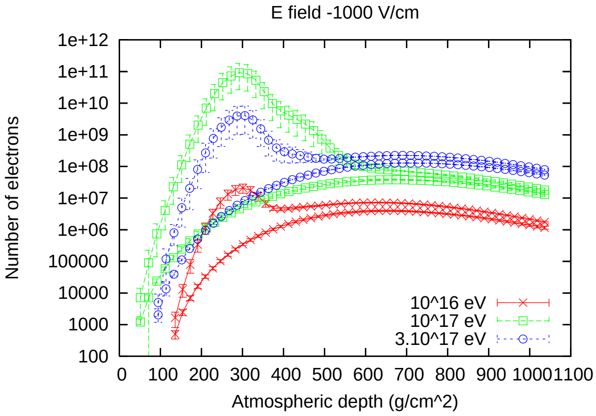

Fig. 2: Number of electrons as a function of atmospheric depth for vertical proton showers of several energies in a background electric field of -1000 V/cm. For each energy the lower line represents the shower development in the absence of a field. The vertical solid line marks the altitude at which the electric field equals the breakeven field.

We use the COAST interface code for CORSIKA [4] to get information on electron and positron distributions at 50 layers evenly distributed in atmospheric depth along the shower axis. At each layer histograms are written out, containing information on the position and momentum of the shower particles.

Fig. 1 shows simulation results for a vertical 10^{16} eV proton air shower. The number of electrons and positrons is plotted as a function of atmospheric depth. The red (solid) lines correspond to the absence of an electric field and the green (dashed) and blue (dotted) lines to fields of 100 V/cm and -100 V/cm respectively. The variations are within the 1 sigma error bars. No significant influence of the electric field on the shower development is observed for this field strength. For fields that are larger by one order of magnitude, however, the influence can be huge.

Fig. 2 shows the shower development in an electric field of -1000 V/cm (accelerating the electrons) for several shower energies. For each energy the lower line represents the same shower in absence of a field. Above the altitude in which the electric field equals the breakeven field [13] an explosive increase in the number of electrons can be seen (note we switched to logaritmic scale). High up in the atmosphere the increase of electrons is nearly exponential. Interestingly, the largest electron content is reached by the shower that had its primary interaction highest up in the atmosphere, not the shower with the highest primary energy. The latter does have the most electrons at lower altitudes, where the breakdown process has stopped and the electrons are injected by pion decay. High up in the atmosphere, the number of electrons increases exponentially reaching a turnover point at $X \approx 300$ g/cm^2, where the electric field is about twice the breakeven field. Note that the point of first interaction for the showers of different energies is random due to the way we selected our showers, and does not follow the dependence of mean first interaction height on primary energy.

An electric field of +1000 V/cm (accelerating the positrons) also strongly influences the energy distribution of positrons and electrons. At some energies the shower can have a positive instead of negative charge excess [21]. In principle, a shower could trigger an upward electron avalanche in such a field, but this does not show up in our simulation as we do not track upgoing particles.

III. REAS2 RESULTS

REAS2 [4] is a Monte Carlo code that calculates the geosynchrotron emission from air showers that are simulated with CORSIKA. For input it uses the histograms produced with COAST. From these distributions REAS2 picks particles, follows a small part of their trajectories and calculates the associated radio emission. In order to do this, an analytic expression for the particle trajectory has to be implemented which gives the particle momentum and acceleration at various points of the trajectory. The electric field effect is included in REAS2 by implementing the equations of motion for a charge inside a homogeneous electric and magnetic field which are under some angle.

The radio emission of air showers is driven by the deflection of electrons and positrons in the magnetic field. When an electric field is present, its contribution to the total radiation can be approximated by comparing the perpendicular component of the electric force to the Lorentz force. Changes in radio pulse height due to an electric field are of the same order of the original pulse height when $E_\perp \sim cB_\perp$. For the geomagnetic field strength in central Europe of $B \sim 0.5$ G, this means an electric field of the order of 100 V/cm can alter the radio pulse height significantly, while fields of the order of 1000 V/cm can dominate the emission mechanism. The geometry of the shower and the fields affects the various contributions. In a shower that propagates parallel to the electric field the charges undergo only linear acceleration, for which the radiation field is suppressed by a factor γ. In a shower that propagates parallel to the magnetic field the charges experience only a small Lorentz force, leading to a small radio pulse. For such showers an electric field can have a relatively large influence.

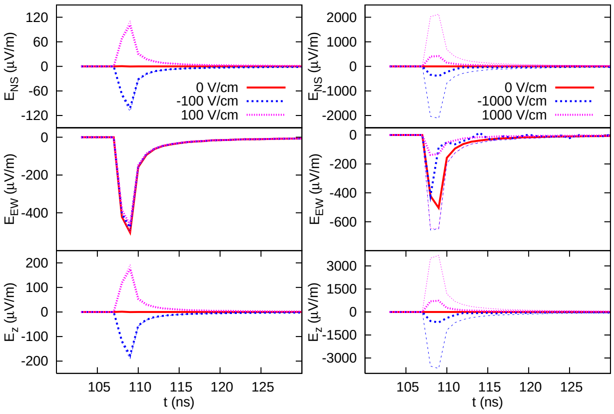

Fig. 3: Radio pulses for an inclined shower (60 degrees zenith angle) of 10^{16} eV propagating towards the north in the presence of electric fields of 100 V/cm (left panel) and 1000 V/cm (right panel). The polarization of pulses in the NS, EW and z directions are shown for an observer located 35 m north of the shower core. Thick lines correspond to simulations in which the electric field effect is switched on in both CORSIKA and REAS2. Thin lines correspond to simulations in which the electric field routine is only switched on in REAS2.

For a single particle, the radio emission is strongly polarized in the direction of the perpendicular component of its acceleration. For the radiation field $\mathbf{A}$ of particle in an electric field $\mathbf{E}$ and magnetic field $\mathbf{B}$ we therefore find:

$$\mathbf{A} \propto (\mathbf{E} - (\mathbf{E} \cdot \hat{n})\hat{n}) + c\,(\hat{n} \times \mathbf{B})\,, \qquad (1)$$

where $\hat{n}$ is the direction of motion of the particle and c is the speed of light. The characteristics of the polarization of the radio emission of full showers, can be roughly explained with this equation.

Fig. 3 shows radio pulses for an observer 35 m north of the shower core for a shower with a zenith angles of 60 degrees propagating towards the north. The three polarization components of the radiation field are plotted separately: north-south (NS), east-west (EW) and vertical (z). For a field of 100 V/cm (left panel) the extra electric field contributions are of the order of the original pulse amplitude, which is to be expected since E and cB are of the same order of magnitude. The polarization properties of the shower radio pulse can be understood in terms of Eqn. 1. Particles propagating towards the north are deflected in the EW direction by the magnetic field, while the electric field deflects the particles in the NS-z plane. The electric and magnetic acceleration give a contribution to the radio pulse in the corresponding polarization directions.

In this particular case, the polarization directions of the electric and magnetic contributions are orthogonal, but this is only true for a shower propagating towards the north or south. In general, the angle between the polarization directions of the two contributions depends on the direction of the shower propagation and the location of the observer. In most cases, the polarization of an air shower radio pulse that has been significantly influenced by an electric field, will be different from a “regular” geomagnetic pulse. For showers propagating towards the east or west, the polarization of the two components is in the same direction, and it not possible to recognize an electric field contribution by studying the polarization only.

In an electric field of 1000 V/cm, where $E \gg cB$, pulses could be produced that are an order of magnitude larger in amplitude than the pulses in the absence of an electric field. Indeed, in the right panel of Fig. 3, such behaviour is visible, but only for the thin lines, which represent a simulation in which electric field effects are only taken into account in REAS2 and not in CORSIKA. When the CORSIKA electric field routine is switched on, the pulse amplitudes in the NS and z plane drop by an order of magnitude. In the EW plane, the pulse amplitudes are even smaller than the pulse amplitude in absence of an electric field. The reason for this drop in pulse amplitude is the direction of motion of the shower electrons and positrons. In a strong field the charges are deflected strongly into the electric field direction. For inclined showers in a vertical electric field, this means that the particles only move into the direction of an observer close to the shower axis for a much shorter part of their trajectories, and less radiation reaches this observer.

Instead, the particles that are deflected into the (vertical) electric field direction will radiate towards different locations on the ground, but these contributions spread out over a large area and will nowhere give emission of significant intensity.

A large production of runaway electrons, such as shown in Fig. 2, will produce additional radio emission that is not simulated in REAS2. The radio emission that is associated with this pulse of runaway electrons is calculated in Gurevich et al. [22] for a vertical shower. Such pulses have a characteristic frequency of 1-10 MHz, and can be much stronger than the pulses we simulate. Detection of such pulses are reported by the Tien-Shan experiment [23]. The timescale of runaway breakdown radio pulses is of the order of microseconds, while the geomagnetic radio pulse is of the order of tens of nanoseconds. In the latter case the pulse is shortened because the the radio waves and particles travel in the same direction, with almost the same speed.

IV. CONCLUSIONS

- For most weather conditions, atmospheric electric fields are not strong enough to significantly influence the radio emission from an air shower. The duty cycle of radio detection of air showers is therefore very high. The technique is reliable in determining the shower energy under all weather conditions except thunderstorms.
- The radio emission of air showers that pass through thunderstorms can be severely influenced by the electric fields present inside the cloud.
- Some other types of clouds, most notably nimbostratus, can contain electric fields with strengths approaching those of thunderstorm electric fields. Although no examples were found in experimental data, we cannot exclude the possibility that such clouds could also have an effect on the radio emission of air showers.
- Pulses that have been influenced by an electric field generally show polarization properties different from pulses that are produced by a pure geomagnetic effect. Polarization measurements therefore contain information of the electric field strength and polarity at a region around the shower maximum.
- An avalanche of runaway electrons can be triggered by an air shower in electric fields exceeding the breakeven field, possibly leading to lightning initiation. The associated fast change in charge distribution can cause strong radio emission.

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