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Shower evolution and radio emission of air showers in thunderstorm electric fields

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Abstract: The radio emission from cosmic ray air showers consists in large part of geosynchrotron radiation. Since the radiation mechanism is based on particle acceleration, atmospheric electric fields may play an important role. LOPES results show that electric fields under fair weather conditions do not alter the radio emission considerably, but during thunderstorms strongly amplified pulses are measured. We simulate the electric field influence on the shower development and radiated emission with CORSIKA and REAS2. We present results from LOPES data analysis and some first results from simulations.

Introduction

The secondary electrons and positrons of an extensive air shower (EAS) produce coherent radio emission in the atmosphere. Results from LOPES [1] show that the intensity of the radio emission is strongly correlated with the angle of the shower axis with the geomagnetic field, proving that the dominant part of the emission is driven by the geomagnetic field. This mechanism can be understood in terms of transverse current emission [2] or geosynchrotron emission [3]. The latter description allows for detailed Monte Carlo simulations in which shower electrons and positrons are treated individually, which is done in [4].

Atmospheric electric fields may influence the emission mechanism, especially when the electric field force is of the same order of magnitude (or higher) as the Lorentz force from the geomagnetic field. The uncertainty introduced by this effect is one of the reasons why efforts to detect radio emission from cosmic ray air showers in the 1970's were abandoned [5]. In this work we discuss the mechanisms by which the electric field influences the emission. Results are shown from LOPES data analysis and Monte Carlo simulations with CORSIKA and REAS2.

Atmospheric electric fields

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. 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 and are typically $100\,\mathrm{kVm}^{-1}$. In most clouds this field is directed vertically (either upwards or downwards, depending on the type of cloud), but thunderclouds contain complex charge distributions and can have local fields in any direction. Thunderclouds can have a vertical extent of $\sim$ 10 km (values taken from [6]).

The atmospheric electric field acts on the radio emission from EAS in various ways. We distinguish two generations of electrons: the relativistic electrons from pair creation in the EAS (called shower electrons from here) and the non-relativistic electrons resulting from the ionization of air molecules by the EAS particles (called ionization electrons from here).

The electric force accelerates the shower electrons and positrons, producing radiation in more or less the same way as the magnetic field does. The total emitted power of a single electron or positron is proportional to the square of the Lorentz factor and the square of the applied perpendicular force: $P \propto \gamma^2 F_\perp^2$. The part of the electric force that is directed perpendicular on the particle orbit adds to the Lorentz force, increasing (or decreasing, depending on geometry) $F_\perp$. The part of the electric force that is directed parallel to the particle orbit increases or decreases γ. Generally, the single particle pulses become stronger but narrower in time. Taking into account coherency effects, this does not automatically lead to amplification of the complete shower pulse. This effect (and the electric field emission mechanism in general) is discussed in detail in [7].

The ionization electrons are also accelerated in the electric field. A radio pulse will be emitted from the current that is produced in this way. When ionized electrons gain an energy of $\epsilon > \epsilon_c \approx 0.1 - 1$ MeV they can ionize new molecules. If the electric field is strong enough to accelerate ionization electrons to such energies a process called runaway breakdown [8] can occur. The critical field strength of $E_c \approx 100 - 150$ kV/m, needed for this effect, is present only inside thunderclouds. The radiation pattern of the runaway breakdown is calculated in [9] for a vertical shower and resembles that of a current pulse. The pulse amplitude is calculated to be several orders of magnitude higher than the geosynchrotron emission from the EAS. Depending on the viewing geometry the pulses can have time widths of 100-300 ns.

Both mechanisms can be responsible for an amplification of the radio pulse from EAS. There are several ways to distinguish between them, including direction of emission, pulse time width and polarization.

LOPES data analysis

In 2004, the LOPES array consisted of 10 east-west aligned dipole antennas, co-located with the KASCADE experiment which provides triggers for LOPES and reconstructs the content, energy and direction of the air shower. When the data used in this paper was taken, LOPES measured only the polarization in the east-west plane. Details about the experimental setup and the reduction of the data can be found in [10].

Three sets of data were selected from the 2004 database of LOPES:

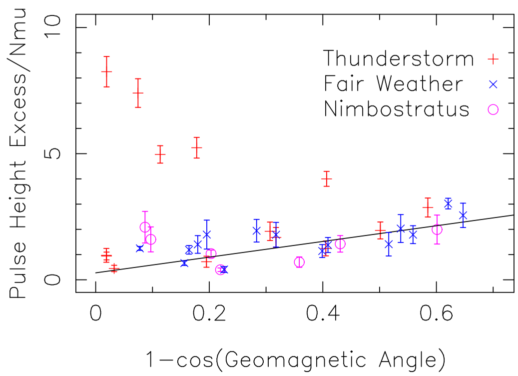

Figure 1: Pulse height, normalized with truncated muon number is plotted against geomagnetic angle. The black line indicates the geomagnetic dependence of the radio emission found in [1]. Pulse heights are given in arbitrary units.

1. Fair weather events which took place during periods with 0% cloud coverage (9455 events spread over the period March-September).

2. Events which took place while the sky was covered by nimbostratus clouds for more than 90% (2659 events spread over the period January-March).

3. Events during thunderstorms, which were identified by looking at lightning strike maps and the dynamic spectra of LOPES, on which the radio emission of lightning strikes show up as bright lines (3510 events taken from 11 thunderstorms in the period May-August).

The weather information is provided by the Karlsruhe weather station. Weather conditions at the LOPES site and the weather station are expected to differ only slightly. Together, all these events form only a very small fraction of the total LOPES database, because the weather information is not complete and even if it was, most weather conditions do not match the criteria of one of these selections. The selections include events for which a radio signal was not detected, i.e. not larger than the background noise by 3 sigma.

In Falcke et al.[1] it was shown that the strength of the radio signal correlates with the geomagnetic angle as $(1 - \cos\alpha)$ when it is normalized with the truncated muon number. This dependence is indicated with a black line in Fig. 1. The events of our three selections that show a significant radio pulse are also plotted in Fig. 1. Events for which the geosynchrotron emission is dominant should be located near the black line. Events that lie a few sigma above this line have a radio signal that is amplified by an additional mechanism. Significant amplification is only observed for thunderstorm events [7].

Monte Carlo simulations

In order to simulate the radio pulse of an air shower in an electric field, two Monte Carlo codes are used, CORSIKA and REAS2. The CORSIKA [11] code, which tracks the evolution of an air shower, has been modified to include an acceleration due to the electric field. This will primarily affect the trajectories of the electrons and positrons. Since accelerated particles will emit bremsstrahlung photons with higher energies which will in turn create new electron-positron pairs this can affect the evolution of the electromagnetic part of the shower considerably.

To calculate the radio emission, particle data output on various levels in the atmosphere is needed. The shower is sampled in 50 layers for each of which four three-dimensional histograms are produced. One kind of histogram contains the particle energy, arrival time and lateral distance to the core and the other kind contains energy, and two angles describing the direction of the particle momentum. Both kinds are created for electrons and positrons.

As an example, Fig. 2 shows the shower evolution for two typical vertical showers of 10^{17} eV, one without electric field and one in a field of 100 kV/m (corresponding to the highest values reached inside thunderstorms). For both cases 10 showers were simulated after which one with a typical shower evolution was selected. The field is directed downwards, meaning it accelerates the shower positrons. When the field is switched on, the number of electrons decreases, while the number of positrons increases. The charge excess switches sign in this case. A field strength of 100 kV/m for the whole sky is unrealistically large and can be regarded as an upper limit.

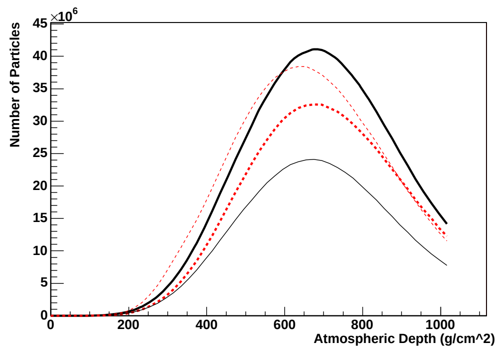

Figure 2: Shower evolution for absent electric field (black/solid) and a field of 100 kV/m (red/dotted). The number of electrons (thick lines) and positrons (thin lines) with energy above 50 keV in a layer are plotted against atmospheric depth.

The radio emission is calculated with REAS2 [12], which uses analytical trajectories for which the initial conditions are taken from the histograms. A new routine has been included in the REAS2 code which calculates analytical trajectories for particles in locally homogeneous magnetic and electric fields, for given field strengths and directions. Since particles are tracked only along a small part of their trajectory inside REAS2 the linear acceleration is not expected to be important at this point. The perpendicular acceleration, on the other hand, will directly affect the amount of radio emission. Fig. 3 shows simulated radio pulses for various electric fields. In this particular case the large electric field results in pulse amplification. This result is not general for different shower parameters and observer positions.

Conclusions

From analysis of LOPES data we find that the relation between the radio pulse and the geomagnetic angle is conserved under all weather conditions but thunderstorms. This means that radio detection of cosmic rays can be used for a reliable shower energy measurement in all but the most severe weather conditions. Currently we are simulating the electric field effects with CORSIKA and REAS2. A detailed description of the implementation of electric field routines into these codes and an analysis of simulation results will be the subject of a forthcoming paper.

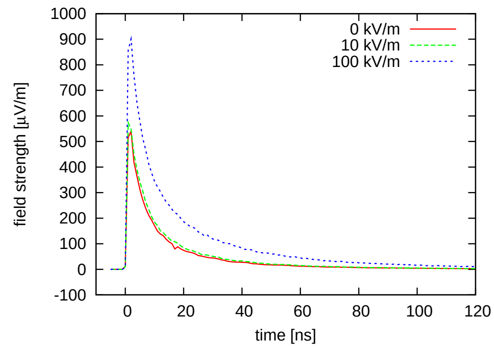

Figure 3: Radio pulses at 50 m to the east of the shower core for a 10^{17} eV shower in various electric fields.

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