Radio-Emission from Cosmic Ray Air-Shower - A Theoretical Perspective for LOPES

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Abstract.
High-energy cosmic ray air-showers have been known for over 30 years to emit strong radio pulses in the regime between a few and several 100 MHz (Allan 1971). To date, however, a thorough analysis of the emission mechanisms has not yet been conducted. Adopting a simplified shower geometry and electron-positron energy distribution, we calculate theoretical pulse spectra in the scheme of synchrotron emission from highly relativistic \( e^\pm \) pairs gyrating in the Earth’s magnetic field. These calculations will play an important role for the calibration of observational data of radio-emission from cosmic ray air-showers acquired with LOPES and later LOFAR and SKA.

1. Introduction
The pulsed radio-emission from high-energy cosmic ray air-showers allows to study their physics with forthcoming digital radio-interferometers such as LOFAR – an approach offering a number of advantages over other methods (Falcke & Gorham 2002, hereafter FG02). The aim of the LOPES project is to develop and test the necessary hardware, software and techniques for future implementation in LOFAR. Additionally, a thorough understanding of the underlying emission processes is necessary to interpret and calibrate the observational data. Past modeling efforts for radio-emission from cosmic ray air-showers have concentrated on scenarios such as charge-separation and transverse currents induced by the Earth’s magnetic field (Kahn & Lerche 1966). An equivalent, but conceptually more attractive and flexible approach is the scenario of coherent synchrotron emission from \( e^- \) and \( e^+ \) gyrating in the Earth’s magnetic field.

2. Emission process and model calculations
Our emission model is based on standard synchrotron theory for highly relativistic particles as described by Jackson (1975). To circumvent problems associated with retardation effects, the \( E \)-field is calculated in the frequency-domain, \( E(\omega) \), rather than the time-domain, \( E(t) \). The far-field energy spectrum per unit solid angle and unit frequency (\( \propto |E(\omega)|^2 \)) generated by a single \( e^\pm \) pair as a function of the angle of the particle trajectories to the line of sight, \( \theta \), and the curvature radius \( \rho \) (depending on the \( B \)-field and Lorentz \( \gamma \)-factor) is then given by (\( K_\nu \) = modified Bessel-function of order \( \nu \)):

\[
\frac{d^2I}{d\omega d\Omega} = \frac{4e^2}{3\pi c^2} \left( \frac{\omega \rho}{c} \right)^2 \left( \frac{1}{\gamma^2} + \theta^2 \right)^2 K_{2/3} \left\{ \frac{\omega \rho}{3c} \left( \frac{1}{\gamma^2} + \theta^2 \right)^{3/2} \right\}
\]

which takes advantage of the symmetry arising from the pair-wise creation of \( e^- \) and \( e^+ \). \( N \) \( e^\pm \) pairs radiating fully coherently (i.e. simultaneously at the same location) would yield an \( N^2 \) enhancement of this spectrum. If the \( e^\pm \) pairs are spatially distributed, however, their contributions have to be added taking into account the appropriate phase-delays. Compared to the fully coherent case this leads to an attenuation by a coherence-factor \( S(\omega) \) (see Aloiso & Blasi (2002) for an analysis of coherence effects regarding synchrotron radiation). The simplest shower geometry taking into account coherence effects is a line of length \( d \) (given by the typical thickness of the air-shower “pan-cake” at its maximum development and set to 2 m here) on which the \( N \) radiating \( e^\pm \) pairs are uniformly distributed. A more realistic Gaussian distribution of the \( e^\pm \) pairs along the line is also considered. The air-shower maximum consists of approximately \( E_p/\text{GeV} \) particles with a mean \( \gamma \) of 60 (see, e.g., Allan 1971). The simplest approximation then is to set \( \gamma \equiv 60 \) for all \( e^\pm \). As a more realistic energy distribution, we adopt a broken power-law rising
will distribute most of the particles away from the shower of the air-shower emission on the ground. One has to keep reconstructed as the Fourier-transform of $S_R$.

With distance $R$ should be able to easily detect (SNR > 100 MHz (see FG02) and the formula over-predicts the experimental results have been described by an empirical results is encouraging, and the next step will be to incorporate a more realistic geometry for the air-shower. All predictions show that LOPES (or a single LOFAR station) should easily be able to detect the radio pulses of a $10^{17}$ eV shower.

3. Conclusions

We have shown that known properties of radio-emission from extended cosmic ray air-showers can be successfully reproduced using the approach of coherent synchrotron emission from $e^\pm$ pairs gyrating in the Earth’s magnetic field. The comparison with the FG02 approximation and empirical results is encouraging, and the next step will be to incorporate a more realistic geometry for the air-shower. All predictions show that LOPES (or a single LOFAR station) should easily be able to detect the radio pulses of a $10^{17}$ eV shower.

References


Jackson, J.D. 1975, Classical Electrodynamics, (John Wiley & Sons, New York)