Astroparticle Physics 104 (2019) 64–77

Contents lists available at ScienceDirect

Astroparticle Physics

journal homepage: www.elsevier.com/locate/astropartphys

An analytic description of the radio emission of air showers based on its emission mechanisms

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ARTICLE INFO

Article history:
Received 18 May 2018
Revised 23 July 2018
Accepted 8 August 2018
Available online 14 August 2018

Keywords:
Cosmic rays
Air shower
Radio emission
Lateral distribution

ABSTRACT

Ultra-high energy cosmic rays can be measured through the detection of radio-frequency radiation from air showers. The radio-frequency emission originates from deflections of the air-shower particles in the geomagnetic field and from a time-varying negative charge excess in the shower front. The distribution of the radio signal on the ground contains information on crucial cosmic-ray properties, such as energy and mass. A long standing challenge is to access this information experimentally with a sparse grid of antennas. We present a new analytic model of the radio signal distribution that depends only on the definition of the shower axis and on the parameters energy and distance to the emission region. The distance to the emission region has a direct relation to the cosmic rays mass. This new analytic model describes the different polarizations of the radiation and therefore allows the use of independently measured signals in different polarization, thereby doubling the amount of information that is available in current radio arrays, compared to what has been used thus far. We show with the use of CoREAS Monte Carlo simulation that fitting the measurements with our model does not result in significant contributions in both systematic bias and in resolution for the extracted parameters energy and distance to emission region, when compared to the expected experimental measurement uncertainties. This parametrization also enables fast simulation of radio signal patterns for cosmic rays, without the need to simulate the air shower.

1. Introduction

Ultra-high energy cosmic rays (UHECRs) impinging onto the atmosphere induce huge cascades of secondary particles. Established techniques for their detection are the measurement of the particles of the air shower that reach the ground, the observation of the isotropic fluorescence light emitted by molecules that have been excited by the shower particles [1,2] or by non-imaging air-Cherenkov telescopes that measure the incoherent Cherenkov light produced by the shower particles [3]. Important observables for most analyses of high-energy cosmic rays are their energy and the atomspheric depth of the shower maximum X_{max}, which is an estimator of their mass. In particular the accuracy, i.e., the systematic uncertainty, of the energy measurement is a crucial aspect. The determination of the cosmic-ray energy from stand-alone particle detectors needs to rely on Monte Carlo simulation, where the hadronic interactions have large uncertainties. So far, the best accuracy is achieved with the fluorescence technique, but this is only possible at sites with good atmospheric conditions. Furthermore, precise quantification of the scattering and absorption of fluorescence light under changing atmospheric conditions requires extensive atmospheric monitoring efforts [1].

Another independent method for the detection of cosmic rays is the detection of broadband radio-frequency emission from air showers [4,5]. The radio technique combines a duty cycle close to 100% with an accurate and precise measurement of the cosmic-ray energy [3,6–8], as well as a good sensitivity to the mass of the primary cosmic-ray [9]. In particular, the energy measurement is well-compatible with, and may even outperform, the fluorescence technique in terms of achievable accuracy [10,11]. This is mostly due to the transparency of the atmosphere to radio waves and the corresponding insensitivity to changing environmental conditions, and because the radio-frequency emission can be calculated theoretically via first principles from the air-shower development [12,13].

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https://doi.org/10.1016/j.astropartphys.2018.08.004
0927-6505/

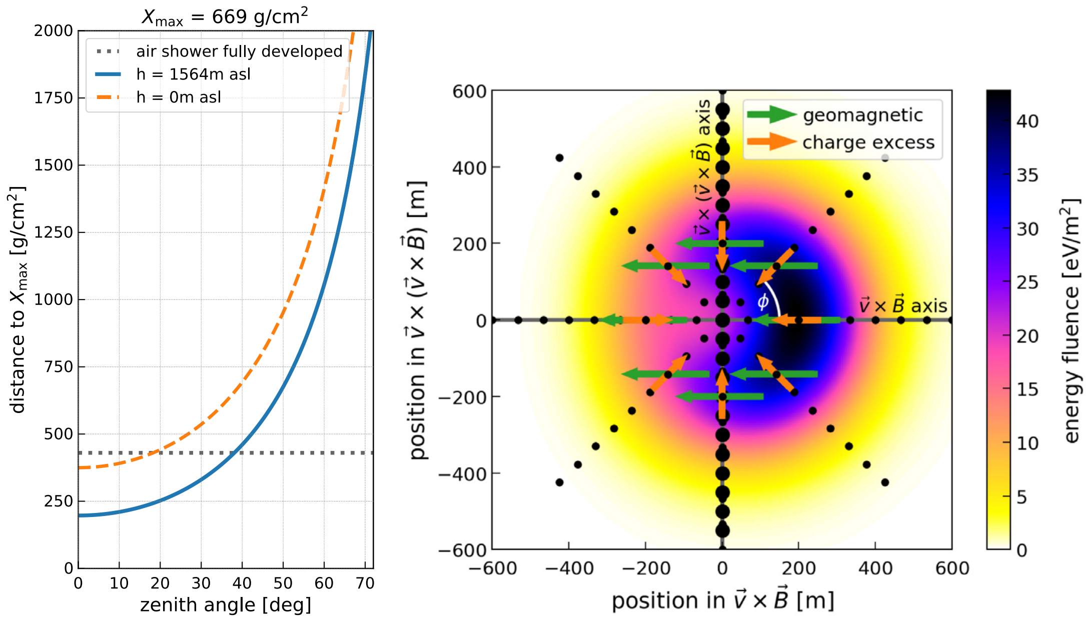

Fig. 1. (left) Distance to X_{max} as a function of the zenith angle for an average X_{max} of 669 g/cm^2 for two observation altitudes. The dotted line shows the distance to X_{max} where the air shower has emitted all its radiation energy. (right) Distribution of the energy fluence (in the 30–80 MHz band) of an air shower with 60° zenith angle at an observation altitude of [1564] m a.s.l., which corresponds to the height of the Engineering Radio Array of the Pierre Auger Observatory. Superimposed is the polarization direction of the geomagnetic and charge-excess emission processes at different positions in form of arrows. The black points show the observer positions for which the radio signal was simulated in CoREAS and the larger black points highlight the axis where the signal can be decomposed into the geomagnetic and charge-excess component.

The radio emission from air showers is due to the acceleration and creation of charged particles within the air shower [14] and is described by classical electrodynamics. In practice, particles other than electrons and positrons do not contribute significantly to the radio emission due to their smaller charge-to-mass ratio [4]. From a macroscopic point of view, radio emission is attributed to two main emission mechanisms: The *geomagnetic* and *charge-excess* emission processes. In the dominant geomagnetic emission process, electrons and positrons are deflected in the geomagnetic field in opposite directions due to the Lorentz force, resulting in a transverse current. The strength of the emission scales with $\sin\alpha$, where α is the angle between the particle movement (shower axis) $\vec{v}$ and the geomagnetic field $\vec{B}$. In the charge-excess emission process, a time-varying negative charge-excess in the shower front leads to a longitudinal current which is mostly due to the knock out of electrons from air molecules.

The spatial distribution of the energy fluence, i.e., the energy per unit area of the radio electric-field pulse, holds information on relevant air shower parameters such as the energy and the atmospheric depth of the shower maximum X_{max} [15]. The amount of energy emitted in the form of radio emission by the air shower – referred to as the *radiation energy* – is given by the spatial integral over the energy-fluence. The radiation energy is directly related to the electromagnetic shower energy E_{em} and allows for a precise measurement with a theoretical energy resolution of only 3% [12]. Thus, the radiation energy serves as a universal estimator of the cosmic-ray energy and is already exploited by the Pierre Auger Collaboration to measure cosmic-ray energies [7,8].

The shape of the spatial signal distribution is primarily determined by the distance $D_{X_{max}}$ from the observer to the emission region. The emission region can be approximated by the position of the shower maximum X_{max} [12]. The distance $D_{X_{max}}$ depends primarily on the zenith angle θ of the air shower and scales approximately with $D_{X_{max}} \propto 1/\cos\theta$, with a second order dependence on the value of X_{max} for the typical physical range of X_{max} [12]. The dependence is visualized in Fig. 1 left. The usage of $D_{X_{max}}$ has the advantage that a universal description of the radio signal distribution can be given that does not depend on the specific altitude of the experiment.

A long-standing challenge to access the energy and X_{max} information experimentally with a sparse grid of antennas is an analytic modeling of the radio signal distribution and will be addressed in this article. In [16], an empirical parametrization for the spatial radio signal distribution is introduced based on morphological arguments, which gives an adequate description of the data measured by LOFAR and the radio array of the Pierre Auger Observatory (AERA) and was already successfully exploited to measure cosmic-ray energies [7,8]. However, explaining the behavior and value of the parameters of this parametrization is not straightforward, as most parameters depend on various shower features. With the knowledge gained over the past years (e.g. [12,16,17]), we formulate an analytic description of the spatial signal distribution directly based on its physical emission processes whose parameters directly depend on the air-shower parameters energy, incoming direction and X_{max}. In addition, we explicitly use the polarization of the radio signal which effectively doubles the available information of each antenna station. This is achieved by the following approach:

We model the spatial signal distribution on the ground originating from the geomagnetic and the charge-excess emission separately. Then, the two signal-strength distributions are both radially symmetric around the shower axis [12]. We note that for inclined air showers an additional asymmetry due to the projection of the signal distribution on the ground arises. This imposes no principle problem for our approach but requires an additional correction of the projection effect first. Hence, we restrict our analysis to air showers with zenith angles smaller than 60° where the projection effect is still negligible. Then, the asymmetric two-dimensional radio signal distribution is modeled naturally by the interference of the two emission mechanisms. This is because the two emission mechanisms exhibit distinct polarization signatures. The geomagnetic emission is polarized in the direction of the Lorentz force $\vec{v} \times \vec{B}$ acting on the shower particles. The charge-excess emission, in contrast, is polarized radially towards the shower axis.