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Evidence for the charge-excess contribution in air shower radio emission observed by the CODALEMA experiment

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ABSTRACT

CODALEMA is one of the pioneer experiments dedicated to the radio detection of ultra high energy cosmic rays (UHECR), located at the radio observatory of Nançay (France). The CODALEMA experiment uses both a particle detector array and a radio antenna array. Data from both detection systems have been used to determine the ground coordinates of the core of extensive air showers (EAS). We discuss the observed systematic shift of the core positions determined with these two detection techniques. We show that this shift is due to the charge-excess contribution to the total radio emission of air showers, using the simulation code SELFAS. The dependences of the radio core shift to the primary cosmic ray characteristics are studied in details. The observation of this systematic shift can be considered as an experimental signature of the charge excess contribution.

1. Introduction

In 1965, Jelley [1] experimentally demonstrated that air showers initiated by high-energy cosmic rays produce strong radio pulses that can be detected between some hundreds of kHz and 300 MHz. Different mechanisms were proposed to interpret this phenomenon. Two main processes responsible for the air shower radio emission are suggested in [2]: the radiation from the net charge excess of electrons in the shower, initially predicted by Askaryan [3], and a geomagnetically induced transverse current in the shower front. It is also pointed out in [3] that the extensive air shower (EAS) radio emission is coherent for wavelengths larger than the characteristic dimensions of the emissive zone. This coherence condition is fulfilled below 100 MHz, which corresponds to wavelengths larger than few meters, comparable to the pancake thickness. At last, Kahn and Lerche [2] predicted that the dominant contribution is the transverse current's one.

These last years, important efforts made on EAS radio emission modeling have permitted to converge toward a consensus about the expected EAS radio signal in the MHz range [4–7]. Prediction of [1–3] were confirmed by modern experiments such as CODALEMA [8,9], LOPES [10,11] and LOFAR [12,13] in the northern hemisphere or RAuger [14] and AERA [15] in the southern hemisphere: the dominant mechanism is due to the geomagnetic field. It implies a strong asymmetry in the counting rates as a function of the arrival direction, at energies near the detection threshold. In addition to this mechanism, the excess of electrons with respect to the positrons is another source of electric field [16]. Indeed, there are more electrons than positrons in the shower due to the in-flight positron annihilation and because electrons are extracted from the medium through Compton, Bhabha and Moeller scattering. First experimental indications for a non-geomagnetic contribution at the levels of (15 ± 5)% and (14 ± 6)% at a frequency of 22.5 MHz, have been reported in the 1970s in [17,18], respectively. In Argentina, between 30 and 60 MHz, this non-geomagnetic contribution has been re-investigated in much more details by the AERA experiment [15], using the polarization measurements in the two east–west (EW) and north–south (NS) horizontal directions. It contributes at a level of (14 ± 2)% in excellent agreement with the past results and is in all aspects compatible with the emission expected from the charge-excess mechanism. Most recently, a detailed investigation of the charge excess fraction has also been published by the LOFAR experiment in [19]. It is shown that the measured charge excess fraction depends on the arrival direction and that it is higher for air showers arriving from directions close to the zenith. Furthermore, it is also measured that

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the charge excess fraction increases with increasing observer distance from the air shower symmetry axis.

In this work, we use a new observable to assess the contribution of the charge excess in the total EAS radio signal. This observable is the discrepancy between the shower core derived from the lateral distribution function of the particle density (the particle core) and the shower core defined by the lateral distribution of the electric field strength (the radio core). The difference between these two core positions is a direct indication of the contribution of the charge-excess contribution as reported in [20]. In [21], we reported for the first time this observation using the data from the Nançay radio-decametric array (DAM) coupled with CODALEMA. The antennas used in the DAM are of a different kind and their characteristics can be found in [22,23]; at that time, we used a selection of 284 showers well reconstructed by the CODALEMA particle detector array that were also detected by 18 dedicated antennas of the DAM. To study the distribution of the electric field with the axis distance, all values of the 284 events measured by the 18 DAM antennas are reported in the shower core reference frame deduced from the particle detectors, rescaled by the estimated primary energy. The average electric field distribution is shown in Fig. 1. We observed that the maximum of the distribution of the electric field is shifted to the east with respect to the origin of the particle reference frame. No satisfactory explanation of this shift could be given at that time.

In this paper, we present the details of the analysis performed using the CODALEMA2 radio array composed of dipolar antennas, described in Section 2. In Section 3, we describe the core reconstruction methods used in CODALEMA and we present the observed shift between the particle core and the radio core. Using simulated showers, we argue that this shift is due to the contribution of the charge excess mechanism. We first explain the origin of the shift in Section 4 and we show the sensitivity of this observable to the shower arrival direction, energy, geomagnetic field orientation and shape of the detection setup. In Section 6, we characterize and compare the core shift of the CODALEMA data set to a simulated data set having the same characteristics, on an event by event basis.

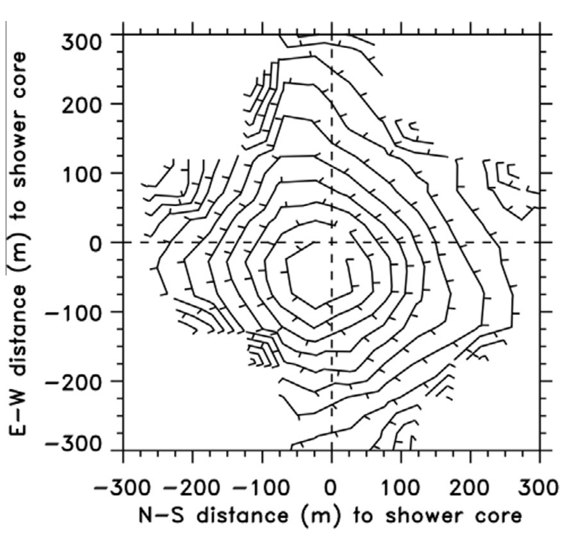

Fig. 1. Electric field distribution at the ground level, in a reference frame centered on the particle shower core, with the *x*-axis aligned with the north–south direction and the *y*-axis aligned with the east–west direction. The distribution has its maximum located at the east of the particle shower core. The figure is extracted from [21].

2. Experimental setup

The CODALEMA2 setup is described in details in [8,9]. We remind here the main characteristics of the experiment. It is worth noting that this setup has been removed and replaced by the so-called "CODALEMA3" array of 57 autonomous radio detection station since 2010. The data set described in Section 3.1 thus covers the period 2006 to 2011. The CODALEMA2 radio detector array is composed of 21 EW-polarized and 3 NS-polarized antennas spread over an area of 600 m $\times$ 500 m (see Fig. 8 farther in this parper). The frequency range used for the data analysis is 23–83 MHz in order to get rid of the AM and FM bands. This radio array is triggered by a particle detector array, made of 17 scintillators covering an area of 340 m $\times$ 340 m. The typical distance between two neighboring scintillators is 80 m. The signal in a scintillator is recorded with a dynamics from 0.3 VEM to 3000 VEM, the VEM (Vertical Equivalent Muon) being the mean charge deposited by a single muon crossing the scintillator vertically. The particle and radio signal are digitized at 1 GHz over 12 bits by MATACQ ADC boards [24] during 2.56 μs. The trigger of the particle array requires that the 5 central scintillators have a signal higher than 0.3 VEM within 600 ns. When this condition is fulfilled, the timing information and signal data from all the detectors (antenna array and particle array) are digitized and read out for further analysis.

The scintillator array data permits to reconstruct the shower arrival direction by multilateration assuming a plane shower front. The shower size at the ground level and the core position are calculated using the estimated particle densities in the scintillators using the Nishimura–Kamata–Greisen (NKG) lateral distribution function [25]. The energy is estimated using the Constant Intensity Cut [26] and we consider events well contained within the particle array (internal events) detector to avoid edge effects biases in the reconstruction procedure.

3. Experimental results

3.1. The data set

We construct a high quality subset of events putting stringent conditions. For the particle reconstruction, we select events with an energy above $10^{16.5}$ eV. We require an angular difference between the arrival directions estimated from both arrays smaller than 20°. The times of impact at a common reference point measured by both arrays must be in the same time window of ±100 ns. We also require that the event core position estimated by the particle array is fully contained inside the particle array. These so-called "internal events" are such that the scintillator with the highest signal is surrounded by active and triggered scintillators. This guarantees a good reconstruction of the shower (core position and shower size). Simulations have shown that the reconstructed parameters suffer from large errors for external events. We keep event having at least 5 antennas with a clear signal; this condition allows to estimate the error on the radio core position in both *x* and *y* directions. For the radio reconstruction (core position and on-axis electric field, see Section 3.3), we select events having a χ^2/dof smaller than 10. There are 216 events passing these cuts (see [9,27]).

3.2. Particle core position

The particle core is defined as the intersection between the ground level plane and the shower axis. The particle lateral distribution function (pLDF) depends only on the distance to the shower axis *d* for zenith angles smaller than 60° and we have used the NKG function to describe it. The particle core position (x_c^p, y_c^p) is