Observation of Polari"{z}ed Microwave Emission from Cosmic Ray Air Showers

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We report on the first direct measurement of the basic features of microwave radio emission from extensive air showers. Using a trigger provided by the KASCADE-Grande air shower array, the signals of the microwave antennas of the CROME (Cosmic-Ray Observation via Microwave Emission) experiment have been read out and searched for signatures of radio emission by high-energy air showers. Microwave signals have been detected for more than 30 showers with energies above $3 \times 10^{16}$ eV. The observations presented in this Letter are consistent with a mainly forward-beamed, coherent and polarised emission process in the GHz frequency range. An isotropic, unpolarised radiation is disfavoured as the dominant emission model. The measurements show that microwave radiation offers a new means of studying air showers at very high energy.

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Introduction – Since the pioneering studies in the late 1960s it has been known that extensive air showers produce an electromagnetic pulse in the kHz and MHz frequency range in the Earth’s atmosphere. With the availability of much more powerful electronics and improved shower simulation methods the study of radio signal emission of air showers has been receiving increasing attention in recent years. Several new experiments have been set up to study the characteristics of the radio signals and different theoretical approaches were developed to understand the origin of this radiation.

Extensive air showers consist of a disk of high-energy particles traversing the atmosphere. With the thickness of this disk being of the order of 1 m, charged particles are expected to emit electromagnetic waves coherently at frequencies below about 100 MHz. It is now understood that the observed radio signal stems from several emission processes. First of all the electrons and positrons of the shower disk are deflected in the Earth’s magnetic field (geomagnetic radiation). Secondly, there are about 20–30% more electrons than positrons in the shower disk leading to a varying charge excess and, hence, electromagnetic radiation (Askaryan effect).

Until recently, radio emission from air showers in the GHz range has not been considered a promising detection channel as the typical wavelengths are in the cm range. Correspondingly very few measurements exist. Early attempts covering frequencies up to 550 MHz confirmed the strong, exponential suppression of higher frequencies. In one of the balloon flights of ANITA (Antarctic Impulsive Transient Antenna), radio signals of extensive air showers were discovered serendipitously and found to extend even up to 900 MHz (see also).

In addition to the aforementioned emission processes, a third source of GHz radiation could be present in air showers. Gorham et al. pointed out that the numerous slow electrons from ionisation produced by the high-energy particles of the shower disk are expected to emit molecular bremsstrahlung at GHz frequencies. Several experiments were set up to search for such a signal with test beams and air shower detectors. First unambiguous detections of microwave signals of air showers in the 3–4 GHz range were reported recently by two of these experiments, EASIER at the Pierre Auger Observatory and CROME.

In this work we present the first study of the basic features of the microwave radiation of air showers using data of the CROME experiment. We show that the
emission takes place mainly within the Cherenkov ring around the shower axis. Comparing the CROME data with theoretical predictions we conclude that the observations are compatible with a superposition of geomagnetic and Askaryan emission processes. Possible applications of the GHz radiation include the measurement of extensive air showers at very high energy with a duty cycle of virtually 100\% as compared to typically 15\% for experiments using Cherenkov light.

The CROME Experiment – The CROME experiment [26] is located within the KASCADE-Grande air shower array [28] at the Karlsruhe Institute of Technology. It consists of different radio antennas covering a wide range of frequencies. The readout of the antennas is triggered by KASCADE-Grande, which is optimised for the detection of air showers in the range from $3 \times 10^{15}$ to $10^{18}$ eV. The trigger signal for CROME is built on a coincident measurement of the three innermost clusters of KASCADE-Grande stations.

The data reported in this article were taken with antennas measuring in the extended C band (3.4–4.2 GHz) range. These C band detectors consist of a parabolic reflector of 335 cm diameter ($\sim 40$ dBi gain) and a multi-receiver camera. In total three antennas of this type were installed and operated over different periods of time between May 2011 and November 2012. One antenna was directed vertically upward and the other two were tilted relative to the first one by $\pm 15^\circ$ with respect to magnetic North.

The cameras were equipped with 9 linearly polarised C band receivers consisting of reflector-matched feed horns and low noise blocks (LN Bs, Norsat 8215F). The receivers were arranged in a compact $3 \times 3$ matrix in the focal plane of the reflector. The four corner feed horns were equipped with a second LNB in each camera during summer 2012, allowing the measurement of two polarisation directions for the same signal direction.

The radiation pattern of the antenna system was measured with a calibrated airborne transmitter [20]. The difference between the main and side lobe of the receivers is more than 10 dB even in off-center channels which are affected by aberration effects. The half-power beam width is less than $2^\circ$ for all channels. The estimated system noise temperature is about 50 K.

A logarithmic power detector (amplifier) was used to measure the envelope of the antenna signals within an effective bandwidth of $\sim 600$ MHz. The response time of the complete system is $\sim 4$ ns (exponential time constant), allowing the measurement of even very short pulses. The signal is digitised and stored for 10 µs before and after the trigger delivered by KASCADE-Grande.

The reconstructed arrival direction, core position, and energy of the showers recorded by the KASCADE-Grande array are used in the further analysis. The reconstruction accuracy is about $0.8^\circ$ for the arrival direction, approximately 6 m for the core position and about 20\% for the energy if the standard quality cuts are applied [28].

![Figure 1. Power received by the logarithmic amplifier as function of time relative to the KASCADE-Grande trigger. Shown are the event with the highest signal (top) and a stereo event (bottom). The signal thresholds of 8 dB are shown as dashed lines.](image)

**Event selection** – We have analysed all reconstructed events passing the KASCADE-Grande quality cuts measured up to August 10, 2012. From these events, we selected the showers crossing the field of view of at least one CROME receiver (approximately 5.5 showers above $3 \times 10^{16}$ eV per day) for which a cone of half-width of $2^\circ$ was assumed.

The expected arrival time of the microwave signal from each air shower was calculated using the reconstructed air shower geometry, accounting for the altitude-dependent refractive index and the measured signal propagation times in the detectors. The typical uncertainty of the signal arrival time due to measurement, reconstruction, and simulation uncertainties is about 50 ns. The strength of a signal in the estimated time window is quantified relative to the mean noise level of each 20 µs trace.

Selecting events with a pulse amplitude of more than 8 dB above the mean trace voltage and energy above $3 \times 10^{16}$ eV we have found 35 showers with a microwave signal. Two of those showers produced a signal above the threshold level in two microwave receivers with the predicted time ordering. The expected number of noise signals above 8 dB is estimated from data by repeating the analysis for shifted time windows and it is found to be $7.1 \pm 1.6$.

A signal with an amplitude of more than 10 dB, corresponding to more than $5 \sigma$ significance for the observed baseline fluctuations within a 50 ns time window, was
measured for 8 events. For the given time interval no noise signal of the same strength is expected.

The time traces of microwave signals measured for two air showers are shown in Fig. 1. The top panel shows the largest signal, 17.7 dB above the noise level, measured with the CROME experiment. The energy of the shower was \( 2.5 \times 10^{17} \) eV with a zenith angle of 5.6° and a core distance of 120 m to the antenna. A shower measured in two receivers of two different antennas (stereo event) is shown in the bottom panel. The shower parameters are: 3.7 \times 10^{16} \) eV, zenith angle 3.7° and core distance 110 m. Very good agreement is found between the measured and calculated time differences for the signals in the two independent antennas in the case of the stereo event.

Properties of the microwave signal – The duration of the microwave signals is about 10 ns. Based on the shower geometry and field of view of the corresponding receivers it can be concluded that most of the signals were emitted from altitudes close to the expected maximum of shower development (typically 4 km above the ground).

In Fig. 2, the distribution of the viewing angle for showers passing the KASCADE-Grande and geometry selection criteria. The red histogram shows the events with a microwave signal greater than 8 dB. The black histogram shows all other events.

Figure 2. Distribution of the viewing angle for showers passing the KASCADE-Grande and geometry selection criteria. The red histogram shows the events with a microwave signal greater than 8 dB. The black histogram shows all other events.

In Fig. 2, the distribution of the viewing angle (the angle between the shower axis and the boresight of the receiver) is shown for events passing the shower selection criteria. The red line indicates the distribution of the viewing angle for receivers with a signal above 8 dB and the black line for all other receivers. One can clearly notice a lack of events in the signal distribution at viewing angles larger than 4°. With a receiver field of view of \( \sim 2° \) the observed angles are compatible with the Cherenkov angle in air (\( \sim 1° \)).

In addition, the core position of events with microwave signal form a ring structure at a distance of 70–150 m around the antennas (cf. Fig. 3). All these features favour an emission mechanism with properties similar to Cherenkov radiation as the dominant source of the observed GHz signals.

Interpretation – For a comparison of the measured events with predictions for the radio signal expected due to the geomagnetic and Askaryan emission mechanisms we improve the purity of the event sample. By considering only events with a viewing angle less than 4° (cf. Fig. 2) we obtain 30 showers (two of which were observed with two receivers) for an expected number of 1.2 \pm 0.5 noise signals. For these events, the positions at which the GHz signal is detected relative to the shower core are given in Fig. 3.

By applying the end-point formalism \( [29] \), CoREAS \( [8] \) allows the simulation of the radio emission associated with acceleration of charged particles in extensive air showers (i.e. including signals due to both the geomagnetic and Askaryan effects). At GHz frequencies, the predicted electromagnetic pulses form a Cherenkov-like cone in the forward direction. The electric field has its highest amplitude on a ring at a distance of 100 \pm 20 m.
The radius of this ring structure is directly correlated with the depth of shower maximum \( X_{\text{max}} \).

The expected electric field strength of a radio pulse calculated with the CoREAS simulation package for a vertical shower is shown in Fig. 2 to illustrate basic features of the expected radio signal at ground. The predicted electric field is shown for two vertical showers of \( 10^{17}\) eV: a typical shower with the depth of maximum at \( X_{\text{max}} = 658\) g cm\(^{-2}\) (upper panel) and a deep proton shower with the shower maximum at \( X_{\text{max}} = 895\) g cm\(^{-2}\) (lower panel). Both the structure of the Cherenkov-like ring and the asymmetries observed in data are qualitatively well reproduced by the typical shower.

In CoREAS, the major emission mechanism in the GHz range is the geomagnetic process with a small contribution coming from the time varying charge excess (Askaryan process). Considering nearly vertical showers, the superposition of the mainly east-west polarised electric field of geomagnetic radiation with the radially inward polarised field due to the Askaryan effect leads to a pronounced east-west asymmetry in the overall signal strength. This asymmetry is confirmed by the data taken with the vertically upward pointing antenna (open symbols in Fig. 3), which has the largest exposure of all three CROME antennas. There are 14 and 3 events detected with the antenna east and west of the shower core, respectively.

The statistics of events measured with tilted antennas (filled symbols in Fig. 3) is dominated by the antenna pointing towards north. The angle between this antenna and the local geomagnetic field vector is about 40°. No significant east-west asymmetry is observed in the core distribution measured by this antenna which can be expected for an increasing dominance of geomagnetic emission. The event rate measured by the antenna pointed almost parallel with the local geomagnetic field vector is much smaller than in the other two antennas.

A detailed comparison of the observed signal amplitudes with the CoREAS predictions can only be done after a full end-to-end calibration of CROME and is beyond the scope of this article.

To compare the measured polarisation directions with CoREAS predictions we simulated showers for each observed event matching the geometry, energy, and muon number reconstructed with KASCADE-Grande. In Fig. 4 the polarisation directions of the receivers with a microwave signal are shown together with those obtained from the CoREAS simulations.

The polarisation information can be compared directly with the CoREAS prediction for the three events detected with dual-polarised receivers. It is found that the signal was always detected only in the receiver with the polarisation direction close to that predicted in the simulations, but the statistics of such events is too small to draw conclusions.

Therefore we applied a detector simulation to the time traces obtained from the CoREAS simulations and calculated the loss in detectable power due to the projection of the predicted electric field vector onto the polarisation direction of the receivers (polarisation loss). The polarisation loss must be small particularly for showers with lower energies. A large number of events was indeed detected in receivers whose polarisation direction matches favourably the local electric field vector of the shower.

Assuming that the time-dependent local electric field vector is correctly described by the CoREAS predictions we find an average polarisation loss of 38\%. For unpolarised pulses from incoherent radiation with a flat frequency spectrum, an average polarisation loss of 50.0\% ± 2.5\% would be expected. Therefore the comparison with CoREAS yields a significance of 5\( \sigma \) that the radiation is not unpolarised. The agreement between the polarisation pattern predicted by CoREAS and our measurements is also better than that of other simplified models, e.g. linear polarisation along the east-west, north-south, and radial directions.

Finally, we also studied high-energy events with a favourable geometry but without a detected microwave signal above 8 dB. We found that the lack of microwave signals could be explained by the large angles between the polarisation directions of the receivers and those expected for the corresponding air showers.

Conclusions and Outlook – Using showers measured with CROME in coincidence with the KASCADE-Grande air shower array we have determined fundamen-
tal properties of the microwave emission of air showers in the forward direction. The spatial and angular distributions of the microwave signal resemble those expected for Cherenkov light emission. The collected polarisation information is incompatible with the hypothesis of an unpolarised signal at the $5\sigma$ level.

A comparison with CoREAS simulations showed that the measurements are qualitatively in good agreement with the extension of the well-known radio emission processes at tens of MHz into the GHz range due to the time compression of the signal close to the Cherenkov angle \cite{11, 13, 19}. We conclude that the measurements favour a coherent emission process that is dominated by an emission region close to the depth of shower maximum. These findings, however, do not exclude a subleading signal component due to an isotropic emission process as expected for molecular bremsstrahlung.

Benefiting from the low background noise and the nearly perfect transparency of the atmosphere at microwave frequencies, as well as the availability of a well-developed technology of microwave detection \cite{20} one can envisage various applications of measuring air showers with setups similar to the one presented here.

For example, measurements with setups similar to CROME can serve as experimental cross-check and calibration of the expected signal for the balloon-borne ANITA detector at the South Pole \cite{18}. The forthcoming ANITA measurement campaign will aim at detecting a large number of ultra-high energy cosmic rays by observing their microwave signal reflected off the Antarctic ice.

Additionally, compared to optical detectors such as imaging atmospheric Cherenkov telescopes \cite{31}, the possibility of measuring with a nearly 100% duty cycle and using simple metallic reflectors instead of optical mirrors could make this measurement technique a promising option. For example, measurements with setups similar to CROME can serve as experimental cross-check and calibration of the expected signal for the balloon-borne ANITA detector at the South Pole \cite{18}. The forthcoming ANITA measurement campaign will aim at detecting a large number of ultra-high energy cosmic rays by observing their microwave signal reflected off the Antarctic ice.

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