Measurements and polarization analysis of radio pulses from cosmic-ray-induced air showers at the Pierre Auger Observatory

Daniël Fraenkel¹, for the Pierre Auger Collaboration²

(1) Kernfysisch Versneller Instituut, University of Groningen, NL-9747AA, Groningen, The Netherlands
(2) Av. San Martín Norte 304, (5613) Malargüe, Prov. de Mendoza, Argentina
E-mail: e.d.fraenkel@gmail.com

Abstract. The Auger Engineering Radio Array (AERA) is designed to study the radio emissions from extensive air showers at the Pierre Auger Observatory. The array currently consists of a grid of 23 autonomous radio detector stations that measure the radio emissions from cosmic-ray-induced air showers since April 2011. The array is still under construction and is planned to be extended to 160 stations. The new detection technique provides an augmentation of the existing detectors, improves the sensitivity of the observatory and sheds new light on the shower physics. An analysis of the emission processes based on the polarization of the radio pulses is presented.

1. Introduction

The leading emission mechanism in radio pulses from extensive air-showers is of geomagnetic origin. The particle flux in the shower front, produced by the interaction with the geomagnetic field produces a net drift of charged particles within the shower. The time variation of this drift causes a short transient pulse to be detected by the radio antennas of the AERA [1, 2] stations.

In addition, theory predicts a secondary emission mechanism due to a net time-varying negative charge excess (as predicted by Askaryan [3, 4]) in the shower front [5, 6, 7, 8, 9, 10]. In this paper we outline the indications of this effect that were observed at the Pierre Auger Observatory.

2. The expected effects of charge excess on the radio emission

In this section we give a short description of both the geomagnetic emission mechanism and the charge-excess effect and we show how these effects can be observed.

The Lorentz force – due to the interaction of the charged particles in the shower front with the geomagnetic field – causes a net drift velocity of the positively and negatively charged particles in the shower front. These opposite charges move in opposite directions inducing a net transverse current \( \vec{J} \). The change of particle density in the shower produces a variation in this current leading to a bipolar shaped electromagnetic pulse which has a unidirectional polarization pattern. This leading geomagnetic emission mechanism is known to scale with the sine of the opening angle \( \alpha \) between the shower velocity \( \vec{v} \) along the shower axis and the geomagnetic field.
\vec{B}, and can be described as:

\[ \vec{E}_{\text{geo}}(\vec{p}, t) \propto -\vec{v} \times \vec{B} \propto \sin \alpha, \]  

(1)

where \( \vec{p} \) is the observer position and \( t \) is time. The polarization of this geomagnetic component is linear and the electric field vector is oriented along the direction of the Lorentz force.

The charge-excess effect, with the electric field component \( \vec{E}_{\text{cxx}}(\vec{p}, t) \), has a different polarization pattern than the geomagnetic effect and is not influenced by the geomagnetic field \( \vec{B} \). The excess charge is caused by the knockout of electrons from the atmosphere creating a net negative charge at the shower front that moves downwards and a positive trail that is left behind. The polarization of this effect is linear and the electric field vector is oriented radially with respect to the shower axis.

The complete electric field is a vectorial sum of both effects,

\[ \vec{E}(\vec{p}, t) = \vec{E}_{\text{geo}}(\vec{p}, t) + \vec{E}_{\text{cxx}}(\vec{p}, t). \]  

(2)

The superposition between these two polarization signatures results in a sinusoidal pattern in the observable \( R(\psi) \) such that

\[ R(\psi) = \frac{2 \sum_{i=1}^{N} \text{Re}(\vec{E}^x_{i+n} \vec{E}^y_{i+n}^*)}{\sum_{i=1}^{N} (|\vec{E}^x_{i+n}|^2 + |\vec{E}^y_{i+n}|^2)} \propto \sin \psi, \]  

(3)

where we have replaced \( \vec{E}(\vec{p}, t) \) with the discretized analytic signal \( \vec{E}_{i+n} \). The cosmic-ray-induced radio pulse is extracted from the larger recorded time series such that \( n \) defines its beginning and \( N \) defines the number of samples that it spans. The observer position \( \vec{p} \) has been dropped in favor of the observer-angle \( \psi \) as described in figure 1a.

The polarization pattern of the geomagnetic component is unidirectional but the direction is different from shower to shower because \( \vec{v} \times \vec{B} \) depends on the arrival direction of \( \vec{v} \). Thus the coordinate system is rotated for every shower such that the geomagnetic component lies on the \( x \)-axis, (figure 1a). The observer-angle \( \psi \) is defined as the angle of the observer around the shower core with respect to the \( x \)-axis. We expect a radial (sinusoidal) pattern as a function of the observer angle as can be seen in the EVA \[7\] simulations shown in figure 1b. These particular simulations were done for \( 10^{17} \) eV showers directed perpendicular to the ground plane with an observer distance of \( d = 70 \) meters. The geomagnetic field in these simulations is pointing exactly to the north and has a strength of \( 24.3 \) \( \mu \)T.

3. Data, Analysis and Results

The data presented in this paper are obtained from the AERA stations, situated in the Auger infill array, and the AERA prototype setup located near the balloon launching station.

The data from the AERA prototype were recorded from the May 20th until June 29th, 2011. These data were produced by scintillator triggered stations each equipped with a log-periodic dipole antenna (LPDA) that is sensitive within the 30 to 80 MHz region. The data from the AERA setup were obtained using a self-triggered setup equipped with similar LPDAs. The period of data-taking ranges from April 15th to Sep 15th, 2011. The radio traces from both these setups are digitized at a sampling frequency of 200 MHz.

An atmospheric electric field meter was used at both setups in order to monitor for thunderstorm conditions. The electric fields produced by thunderstorms are known to strongly affect the amplitude and polarization of the pulses. The radio data were used only when the electric field meter showed no significant amplitudes or fluctuations.

The measured data were cleaned using a FIR-filter based on linear prediction that was fine-tuned using the background in order to filter out the periodic RFI.
Figure 1. Observer-angle dependence of the ratio R – The origin in panel a) is at the shower core and the picture of the antenna indicates the observer position. Panel b) shows the expected sinusoidal pattern in $R$ as a function of the observer angle $\psi$.

The shower parameters from the surface Cherenkov detectors were reconstructed with the software package CDAS. Subsequently the electric field was reconstructed using the reconstruction pipeline of the Offline software framework [11], aided by the shower parameters from CDAS.

In order to extract the pulse $S$, a region of interest within the recorded radio traces is identified; an interval with a length of 500 ns known to contain the pulse. The pulse is then found by scanning this region with a smaller sliding window of 125 ns (25 time samples). The amplitude in this sliding window is calculated by averaging the squared sum of the channels and taking the square root. The maximum amplitude yielded by the sliding window is then chosen to be the pulse $S$. Thus we have

$$S = \left( \frac{1}{25} \sum_{i=1}^{25} \vec{E}_i \cdot \vec{E}^*_i \right) / 25,$$

where for every measured trace $n$ is such that $S$ is maximal. The noise level $N$ is determined from a region of 1000 ns (200 samples) within the radio trace that contains only noise:

$$N = \sqrt{\frac{1}{m_1 - m_0} \sum_{m=m_0}^{m_1} \vec{E}_m \cdot \vec{E}^*_m / 200},$$

where $m_0$ and $m_1$ are the start and stop samples of this noise region.

As mentioned earlier, the AERA prototype setup is an externally triggered setup using scintillators to activate the read out of the RDS. This triggering scheme can cause the read out of pulses with amplitudes well below the noise level. In order to obtain a pulse of sufficient quality a signal to noise cut of $S/N > 2$, is applied to the data from the AERA prototype. Because the data from the AERA setup are obtained from self-triggered stations with pulse amplitudes $S$ of at least four times the noise level, this method of data taking does not require such a cut.

The uncertainties in $R$ are obtained by adding noise from the noise region to the pulse such that an ensemble of varied pulses is obtained:

$$\vec{E}'_{i+n} = \vec{E}_{i+n} + \vec{E}_{i+m},$$

for $i$ running from 1 to 25. The values of $m$ effectively enumerate this ensemble and run through the noise region from $m_0$ to $m_1 - 25$. Subsequently an ensemble of values $R'$ is determined.
from $\vec{E}_{++}$ in the same manner as the original $R$ and the variance of this ensemble is taken to be the uncertainty on $R$. The results of this analysis are shown in figure 2 where the discussed sinusoidal pattern is observed.

4. Discussion

The results from the AERA setup and its prototype show a clear radial component in the polarization signature of the cosmic-ray-induced radio pulses. This is what is to be expected for a significant contribution of the time varying charge-excess to the total air-shower radio emission. A paper with further analysis based on simulations is forthcoming.

The AERA setup proves to be an instrument that is capable of doing detailed polarization measurements on air-shower-induced radio pulses. These and future results from this setup, in combination with the existing detectors of the observatory, can have a significant bearing on the understanding of the emission processes and the unraveling of the shower physics.

References

[1] Huege T 2010 Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment 617 484 – 487 ISSN 0168-9002 URL http://www.sciencedirect.com/science/article/pii/S0168900209019172
[2] Abreu P et al. (The Pierre Auger Collaboration) 2011 Proceedings of the 32th ICRC, Beijing China (Preprint 1107.4807)
[3] GA Askaryan 1962 Sov. Phys. JETP 14 441
[4] GA Askaryan 1965 Sov. Phys. JETP 21 658
[5] Huege T, Ulrich R and Engel R 2007 Astropart. Phys. 27 392–405 (Preprint astro-ph/0611742)
[6] de Vries K D, van den Berg A M, Scholten O and Werner K 2010 Astropart. Phys. 34 267–273 (Preprint 1008.3308)
[7] de Vries K D, van den Berg A M, Scholten O and Werner K 2011 Phys. Rev. Lett. 107(6) 061101 URL http://link.aps.org/doi/10.1103/PhysRevLett.107.061101
[8] Ludwig M and Huege T 2011 Astroparticle Physics 34 438 – 446 ISSN 0927-6505 URL http://www.sciencedirect.com/science/article/pii/S0927650510002094
[9] Alvarez-Muniz J, Carvalho Jr W R and Zas E 2012 Astropart.Phys. 35 325–341 (Preprint 1107.1189)
[10] Kalmykov N, Konstantinov A and Engel R 2010 Physics of Atomic Nuclei 73(7) 1191–1202 ISSN 1063-7788 URL http://dx.doi.org/10.1134/S1063778810070136
[11] Abreu P et al. 2011 Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment 635 92 – 102 ISSN 0168-9002 URL http://www.sciencedirect.com/science/article/pii/S0168900211001276