Institute of Physics Publishing Journal of Physics: Conference Series **39** (2006) 471–474
doi:10.1088/1742-6596/39/1/123 TAUP 2005: Proc. Ninth Int. Conf. on Topics in Astroparticle and Underground Physics

Radio emission of highly inclined cosmic ray air showers measured with LOPES - possibility for neutrino detection

J Petrovic[g], W D Apel[a], F Badea[a], L Bähren[b], K Bekk[a], A Bercuci[c], M Bertaina[d], P L Biermann[e], J Blümer[a,f], H Bozdog[a], I M Brancus[c], S Buitink[g], M Brüggemann[h], P Buchholz[h], H Butcher[b], A Chiavassa[d], K Daumiller[a], A G de Bruyn[b], C M de Vos[b], F Di Pierro[d], P Doll[a], R Engel[a], H Falcke[b,e,g], H Gemmeke[i], P L Ghia[j], R Glasstetter[k], C Grupen[h], A Haungs[a], D Heck[a], J R Hörandel[f], A Horneffer[e,g], T Huege[a,e], K-H Kampert[k], G W Kant[b], U Klein[l], Y Kolotaev[h], Y Koopman[b], O Krömer[i], J Kuijpers[g], S Lafebre[g], G Maier[a], H J Mathes[a], H J Mayer[a], J Milke[a], B Mitrica[c], C Morello[j], G Navarra[d], S Nehls[a], A Nigl[g], R Obenland[a], J Oehlschläger[a], S Ostapchenko[a], S Over[h], H J Pepping[b], M Petcu[c], T Pierog[a], S Plewnia[a], H Rebel[a], A Risse[m], M Roth[f], H Schieler[a], G Schoonderbeek[b] O Sima[c], M Stümpert[f], G Toma[c], G C Trinchero[j], H Ulrich[a], S Valchierotti[d], J van Buren[a], W van Capellen[b], W Walkowiak[h], A Weindl[a], S Wijnholds[b], J Wochele[a], J Zabierowski[m], J A Zensus[e], and D Zimmermann[h]

(a) Institut für Kernphysik, Forschungszentrum Karlsruhe, 76021 Karlsruhe, Germany
(b) ASTRON, 7990 AA Dwingeloo, The Netherlands
(c) National Institute of Physics and Nuclear Engineering, 7690 Bucharest, Romania
(d) Dipartimento di Fisica Generale dell'Università, 10125 Torino, Italy
(e) Max-Planck-Institut für Radioastronomie, 53010 Bonn, Germany
(f) Institut für Experimentelle Kernphysik, Universität Karlsruhe, 76021 Karlsruhe, Germany
(g) Department of Astrophysics, Radboud University Nijmegen, 6525 ED Nijmegen, The Netherlands
(h) Fachbereich Physik, Universität Siegen, 57068 Siegen, Germany
(i) Inst. Prozessdatenverarbeitung und Elektronik, Forschungszentrum Karlsruhe, 76021 Karlsruhe, Germany
(j) Istituto di Fisica dello Spazio Interplanetario, INAF, 10133 Torino, Italy
(k) Fachbereich Physik, Universität Wuppertal, 42097 Wuppertal, Germany
(l) Radioastronomisches Institut der Universität Bonn, 53121 Bonn, Germany
(m) Soltan Institute for Nuclear Studies, 90950 Lodz, Poland

E-mail: `petrovic@astro.ru.nl`

Abstract. LOPES - LOFAR PrototypE Station (LOFAR - LOw Frequency ARray) is an array of dipole antennas used for the detection of radio emission from cosmic ray air showers. It is co-located and triggered by the KASCADE (KArlsruhe Shower Core and Array Detector) experiment, which also provides information about air shower properties like electron number N_e, muon number N_μ, azimuth and zenith angle. LOPES-10 (the first phase of LOPES, consisting of 10 antennas) detected a significant number of cosmic ray air showers with a zenith angle larger than 50^o, and many of those have very high field strengths. The most inclined event that has been detected with LOPES-10 has a zenith angle of almost 80^o. This is important, because cosmic ray air showers with large inclinations, triggered close to the ground, would be a signature of neutrino events. Due to the small baseline of the LOPES-10 detector, it is not yet possible to determine accuratelly the radius of curvature of the showers front, which is related to the distance to the maximum of shower development. However, this should be possible in the future with a large baseline radio telescope like LOFAR.

1. Introduction

When a cosmic ray interacts with particles in the Earth's atmosphere, it produces a shower of elementary particles propagating towards the ground with almost the speed of light. The first suggestion that these air showers can produce radio emission was given by Askaryan [1] based on a charge-excess mechanism. Recently, Falcke & Gorham [2] proposed that the mechanism for radio emission of air showers is coherent geosynchrotron radiation: secondary electrons and positrons, produced in the particle cascade, are deflected in the Earth's magnetic field producing radiation that is relativistically beamed in the forward direction. The shower front emitting the radiation has a thickness which is comparable to a wavelength for radio emission below 100MHz (around few meters). The LOPES-10 experiment that detected radio emission from cosmic ray air showers [3] and the data reduction are described in detail by Horneffer et al. [4].

Neutrinos are not very likely to interact within the Earth's atmosphere and produce air showers due to the very small cross section for interactions. The probability for interaction increases with the length of the path through the atmosphere, so the neutrinos that are most likely to trigger air showers are entering the atmosphere almost horizontally, possibly producing very inclined cosmic ray air showers. Inclined showers that start high in the atmosphere (initiated by protons, nuclei or gamma-photons) have a large electron deficiency on ground level compared to the nearly vertical showers, since they travel through several times longer distances in the Earth's atmosphere (large radius of the shower front curvature) and most of the electromagnetic particle component of those showers is absorbed. On the other hand, neutrino induced showers may be generated at any distance from the ground [7] and due to this they still have a significant number of electrons reaching the ground and their shower front curvature radius is relatively small. We should also mention that highly inclined showers are expected to be very well detectable in the radio domain [5],[6].

2. Detection of inclined showers

We found 2017 events with a zenith angle larger than 50^o detected in year 2004 by LOPES-10. There are 1913 triggers from the KASCADE detector for events with zenith angles between 50^o and 70^o and 52 have been detected in the radio domain, which is roughly 1 in 35. With the increase of the zenith angle, the number of triggers decreases and there are only 86 for zenith angles larger than 70^o. Out of those, 4 have been detected by LOPES-10. This detection rate is significantly higher than the average detection rate for LOPES-10, which is roughly 1 event detected in the radio domain per 1000 triggers received from the KASCADE detector. The reason is that inclined showers that manage to reach the ground after traveling long distances must have high energy primary particles.

If we introduce an additional condition: $N_\mu > 10^5$, we narrow the selection to 51 events and around 40% of those are detected in the radio domain. Seven of those events have a radio signal and reliable shower properties reconstructed by the KASCADE detector (KASCADE is not optimized for large zenith angles). As an example, we show here one of those events, detected in March 2004 with a zenith angle of 53.3^o and an azimuth angle of 54.3^o with roughly the same number of electrons and muons $N_e \approx N_\mu \approx 1.5 \cdot 10^6$. The angle between the shower axis and

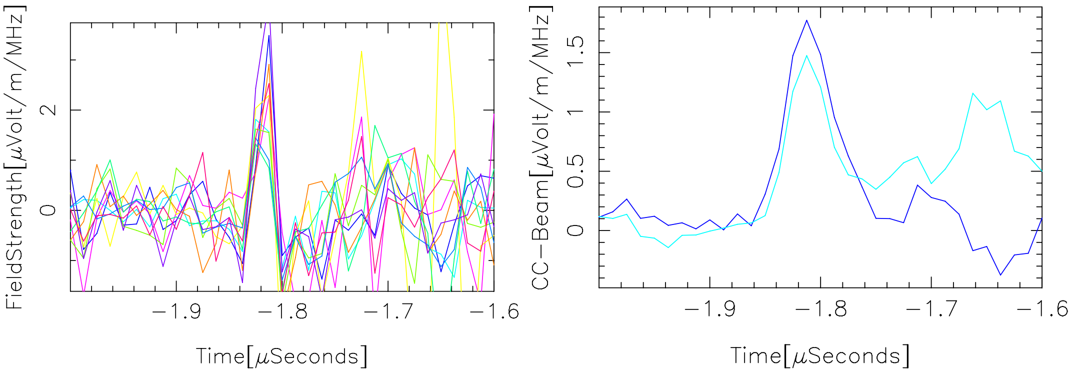

Figure 1. Left: Electric field as a function of time for LOPES-10 antennas for an event detected in March 2004 with zenith angle 53.3^o and azimuth 54.3^o. Geomagnetic angle is 69.8^o and N_e=1.5·10^6, N_μ=1.5·10^6, reconstructed by KASCADE. Right: Radio emission as a function of time after beam forming for the same event. The dark blue line represents CC-beam, the light blue line the total power.

the Earth's magnetic field (geomagnetic angle) is 69.8^o. The energy of the primary particle is estimated by KASCADE to be around 10^{17} eV. In Fig.1 (left panel), we show the electric field as a function of time for each of ten LOPES-10 antennas after being corrected for geometric and instrumental time delay. The field is coherent at -1.825 μs, which is the arrival time of the shower. The incoherent noise afterwards is radio emission from photomultipliers. In this case it is very weak, indicating a low energy deposit in the photomultipliers and low electron number on the ground. The right panel of this figure shows the radio emission as a function of time after CC (cross correlated) - beam forming. This beam is formed in the following way: for a given direction, signals are corrected for a time delay between arrival of signals to each antenna. Then signals of all possible two antenna combinations are multiplied, summed and normalized to the number of antennas.

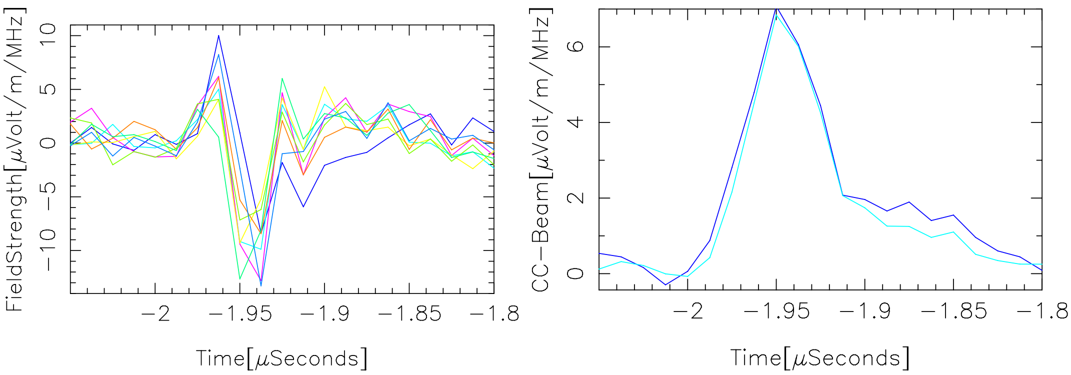

Figure 2. Left: Electric field as a function of time for LOPES-10 antennas for an event detected in January 2004 with zenith angle 77.1^o and geomagnetic angle 83.6^o. Right: Radio emission as a function of time after beam forming for the same event. The dark blue line represents CC-beam, the light blue line the total power.

LOPES-10 has also detected four events with zenith angles larger than 70^o, but due to the very high inclination, shower properties are impossible to reconstruct with the KASCADE detector. We show an example of such an event with a zenith angle of 77^o in Fig.2.

3. Geomagnetic field

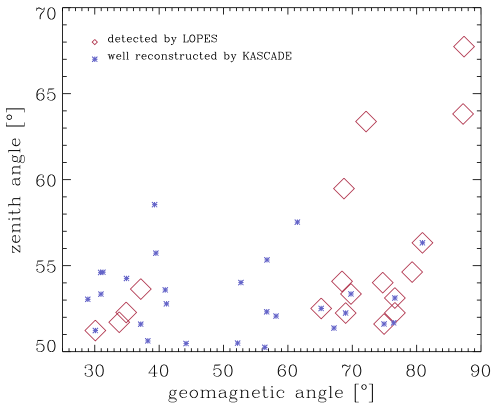

Figure 3. Geomagnetic and zenith angle of inclined events from 2004 ($z{>}50^o$, $N_\mu{>}10^5$) detected by LOPES-10 (rhombs) and well reconstructed by KASCADE (stars). Radio detection clearly depends on a geomagnetic angle, particle detector reconstruction depends on a zenith angle.

In Fig.3 we notice that events that are detected by LOPES-10 (rhombs) have mostly large geomagnetic angles (more than 60^o) and events with a reliable KASCADE reconstruction (stars) have smaller zenith angles. The correlation between radio detection and geomagnetic angle is in agreement with the theory of geosynchrotron origin of radio emission from air showers [2] and with results from [3].

4. Conclusions

While for the particle detector KASCADE sensitivity drops significantly towards larger zenith angles, so there is no well reconstructed event with $z{>}60^o$, that is not the case for radio detection. The most inclined cosmic ray air shower that has been detected with LOPES-10 has a zenith angle of almost 80^o. For a neutrino detection in the radio domain, it is crucial that the detector can see very inclined events and that it can determine the curvature radius of the shower front which is related to the distance to the shower maximum. In this paper, we show that the LOPES-10 array of dipole antennas can detect air showers coming from around 10^o above the horizon.

The radius of a shower front curvature for events detected by LOPES-10 is optimized by iteration until the intensity of detected coherent signal is maximal [4]. This can not be done accurately with LOPES-10, due to the relatively small baseline. However, this will be possible in the future with a large baseline radio telescope like LOFAR. Also, neutrino events are expected to be very rare, for example yearly neutrino rates for all different predicted fluxes, for an array of 3000km^2 are up to few per year [7] and a large baseline is crucial to increase the probability to reliably identify air showers initiated by energetic cosmic ray neutrinos.

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