Air Shower Measurements with LOFAR

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for the Cosmic Ray KSP
Outline

- Cosmic rays and air showers
- Measurement with LOFAR
- Results from LOPES
- Direction determination
- Summary
Cosmic Rays

- High energy particles
- Dominated by hadrons (atomic nuclei)
- Similar in composition to solar system
- Broad range in flux and energy
- Different energy regimes:
  - $<10^7$ eV Modulated by solar wind
  - $<5 \times 10^{14}$ eV Direct detection possible
  - $>5 \times 10^{14}$ eV Indirect detection (air showers)
Air Showers

- High energetic cosmic rays interact with nuclei in the atmosphere
- In a cascade lots of secondary particles emerge
- A “pancake” of particles
- Established detection methods:
  - Air-Fluorescence: Detection of fluorescence light
  - Particle Detector Arrays: Particles that reach the ground
Radio Emission from Air Showers

- Air showers emit short, intense radio pulses, beamed into the forward direction.
- Radiation due to geomagnetic emission process e.g. geosynchrotron.
- Coherent emission at low frequencies.
- Measuring the radio emission from air showers could give several benefits:
  - Higher duty cycle than fluorescence telescopes.
  - Effective RFI suppression allows measuring in polluted (populated) areas.
  - Data integrated over the shower evolution, can be complementary to particle detectors.
  - High angular resolution possible.
LOFAR for Cosmic Rays

- Designed as an astronomical telescope not an air shower detector:
  - “small” stations with lots of antennas in a small area
  - different baselines between stations

- Consequences:
  - low effective area for the number of antennas
  - high sensitivity
  - very good calibration

- This makes LOFAR an unique tool to study air showers:
  - Develop the method (triggering, reconstruction)
  - Understand the emission process
  - Air shower physics (new particles?)
  - Change galactic→extragalactic cosmic rays
LOFAR-CR
Energy Ranges

Flux $E^{2.5} J(E)$ ($m^{-2} s^{-1} sr^{-1} eV^{1.5}$)

Energy (eV/particle)
HECR-Triggering
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- Prototype of a LOFAR station
- Set up inside an air shower array
- Frequency range of 40–80 MHz
- Triggered by particle detectors
- Detection of air showers with LOFAR technology

Falcke et al. (LOPES collaboration), Nature, 435, 313, 2005
Detected Events

- Not all triggered events have a detectable radio pulse
- Fraction of “good” to “bad” events increases with increasing shower size and increasing geomagnetic angle
- Suitable cuts give 100% detection efficiency
Thunderstorm Events

- Does the electric field of the atmosphere influence CR radio signal?
- Increased pulse height during thunderstorms.
- No other effects seen.

Buitink et al. (LOPES coll.) 2007, A&A (in print)
LOFAR

Parametrization

\[
\varepsilon_{est,E_p} = (12 \pm 1.8) \left[ \frac{\mu V}{m \text{ MHz}} \right] (1 + (0.1 \pm 0.03) - \cos(\alpha)) \cos(\theta)
\times \exp \left( \frac{-R_{SA}}{(200 \pm 45) m} \right) \left( \frac{E_p}{10^{17} \text{ eV}} \right)^{(0.91 \pm 0.07)}
\]

(\(\varepsilon_{est}\): EW-pol field strength per unit bandwidth, \(\alpha\): geomagnetic angle, \(\theta\): zenith angle, \(R_{SA}\): mean distance antennas ↔ shower axis, \(E_p\): primary particle energy)
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Sources of Cosmic Rays

New Physics?
Finding Sources of Ultra High Energy Cosmic Rays

- Limited by statistics and angular resolution

→ Need large detectors with good angular resolution!

Large detectors are being built, need angular resolution.
Direction determination with detector arrays

- Measure the arrival time at different positions on the ground
- The relative times gives the direction

Diagram showing a graph with distance on the x-axis ranging from -5000m to 5000m and distance on the y-axis ranging from 0km to 20km.
Direction Determination

- Current resolution: \(~0.5^\circ\) limited by costs (pixel size) and/or physics (quantization)
- Radio signal is smooth, not quantized
- Good timing (phase) calibration of radio antennas possible
- Radio can increase angular resolution from \(~0.5^\circ\) to <0.1°
- Needed work:
  - Study shape of radio pulse front
  - (Timing calibration for large antenna fields)
Summary

- LOPES has proven that LOFAR can measure air showers
- LOFAR is an unique tool for this measurement
  - High sensitivity
  - Excellent calibration
- Interesting new physics
  - Understand the emission process
  - Air shower physics (new particles?)
  - Change galactic $\rightarrow$ extragalactic cosmic rays
  - Direction resolution $\rightarrow$ particle astronomy
Angular dependence

- Pulse height depends on the geomagnetic angle
- After normalization no further dependence on zenith or azimuth angle
Dependencies: Size, $N_{\mu_{\text{trunc}}}$ and Energy

- Only little dependency on electron number
- Power law is a good fit for muon number and energy
Distant events with KASCADE-Grande

Haungs et al. 2006; Badea et al. 2005; Apel et al. (LOPES coll.), Astropart.Phys. 26 p.332
Inclined Showers
($\Theta=50-90^\circ$)

$\Theta \approx 75^\circ$