Radio detection of air showers with LOPES and LOFAR

Next-Generation Techniques for UHE Astroparticle Physics

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A short history

- 1960s: First emission theory charge excess (Askaryan 1962) and geomagnetic radiation (Kahn & Lerche 1967)

- 1970s: Detections by multiple experiments. Efforts are abandoned due to inadequate hardware & theoretical uncertainties.


- 2003+: LOPES (LOFAR prototype station) detects air shower in radio, other experiments follow

- Now: detailed understanding of radiation mechanism. Large experiments: LOFAR, AERA (Auger), Tunka-rex

(see review paper: T. Huege, Phys. Reports, arXiv:1601.07426)
What drives the radio emission?

- **Earth magnetic field**
  electrons/positrons deflected
  \( E \sim \frac{dn_{ch}}{dt} \)

- **Charge excess**
  negative charge due to electron knockouts
  \( E \sim \frac{d(n_e-n_p)}{dt} \)

- **Non-unity index of refraction**
  Cherenkov-like effects
  ring structure possible

Coherent at 100 MHz (higher at Cherenkov angle!)
wavelength > shower front size
\( P \sim n^2 \)
The radio footprint

vector sum of **geomagnetic** and **charge excess** component
relativistic beaming
Cherenkov-like propagation effects (n≠1)

**CoREAS**: Huege et al. AIP Conf Proc 128-132 (2013)
- plugin for CORSIKA
- calculates contribution from each particle
- based on **first principles**
  (no assumption on emission mechanism)
Measuring Xmax
Xmax = atmospheric slant depth of shower maximum (g/cm²)

proton primary
high Xmax

iron primary
low Xmax

1D approach: measure slope (LOPES)
2D approach: fit complete profile (LOFAR)
LOPES technical data

Digital interferometer

Trace length: 0.8 ms

Frequency range

09 June 2014, ARENA, Annapolis

Frequency resolution for relative timing accuracy of ~ 1 ns

Relative position accuracy noise reduction

(2^80 MHz ADC sampling 40-80 MHz Nyquist domain)

LOPES: Radio Wavefront provide a local trigger used in conjunction with the radio antennas. The radio pulse from the extensive air shower correlates strongly between antennas and can thus be clearly identified in the presence of noise from KASCADE particle detectors. Adapted from [67].

Figure 16: Left: Radio signals measured in various LOPES antennas during the arrival of an extensive air shower. The most prominent pulses originate from the high-voltage feeds of the KASCADE particle detectors. The radio pulse from the extensive air shower is smaller in comparison.

While AERA comprises a “sparse array” covering a large area with a homogeneous array of radio antennas, LOFAR can be characterised as a “dense array”. LOFAR is a general-purpose radio astronomy instrument co-located with KASCADE, which is a particle detector array, LORA [80], the core. Independent sets of high-band antennas sensitive to the frequency range of 110 to 240 MHz are co-located to the frequency range of 10 to 90 MHz are distributed over an area of roughly 300 antennas sensitive to the frequency band from 10 to 90 MHz. The radio signals themselves can be used for cosmic ray detection, and the possibility of self-triggering on the radio detectors. In a first phase in 2011, 24 radio detection stations using antennas were deployed on a triangular grid of 144 m. The measurement frequency band was 30 to 80 MHz. Two types of antennas were deployed on grids of 250 and 375 m distance. The sensitivity of radio detection to mass-sensitive parameters will allow a direct cross-check of the sensitivity of fluorescence detectors.

For which cosmic ray detection is only one mode of operation. AERA is a dedicated particle detection and fluorescence detection instrument of the Pierre Auger Observatory. The latter advantages of AERA is its co-location with the very sophisticated particle detection and fluorescence detection instruments of the Pierre Auger Observatory. The latter phases of the actual array. The science goals of AERA are to do the necessary engineering for a larger-scale search in the region of transition from Galactic to extragalactic interactions. AERA was extended by an additional 100 radio detection stations in 2013, an additional 100 radio detection stations on the radio signals themselves. In a second stage in 2015, AERA was extended by an additional 25 radio detection stations for which cosmic ray detection is only one mode of observation. To facilitate cosmic ray detection, triggering will be triggered by a dedicated particle detector array, LORA [80], the core.

LOPES - energy

Analysis at “pivot point”

Energy resolution 20-25%
(combined LOPES - KGrande
KGrande alone ~20%)

Very good agreement
to CoREAS (2%)

Apel et al. PRD 90, 062001 (2014)
LOPES - X_{\text{max}}

based on 1D slope method
statistical uncertainty \sim 50 \text{ g/cm}^2
systematic uncertainty \sim 90 \text{ g/cm}^2
proof of concept: first radio composition analysis!

Apel et al. PRD 85, 071101 (2012)
LOFAR
low frequency array
10 - 250 MHz

Epoch of Reionization
Radio Transients
Astroparticle Physics
Cosmic Magnetism
Surveys
Solar Physics
SUPERTERP
~600 low band antennas
10 - 80 MHz
5 ns time resolution
> GB buffer/antenna

+ LORA
LOFAR Radboud air shower array
20 scintillator stations (ex-KASCADE)

24 core stations
9 remote stations
8 international stations
LOFAR is designed to support many different observation strategies.

CR detection runs in the background during other observations.
Air shower detection with LOFAR

LORA
LOFAR Radboud Array
scintillator detectors

trigger

buffer
2 ms read-out

 offline analysis

LORA (Scintillator)
High-Band
Low-Band

Pim Schellart et al., A&A 560, 98 (2013)
Wavefront curvature

Subtracting the plane wavefront solution, treating curvature as a perturbation gives ~6 ns delays at edge of the array. This can be directly measured with LOFAR. Preliminary results point to mixed spherical / conical wavefront shape. Wavefront curvature may provide measurement of Xmax independent of pulse power

Corstanje et al. (in prep)

antennas grouped in rings
pentagons: LORA scintillators
reconstructed core & direction
station outside superterp
For each LOFAR shower:

- Reconstruct **direction** from antennas (plane wave) + **energy** estimate from particle array (LORA)
- Produce **50 p + 25 Fe** showers
  - CoREAS
  - CORSIKA 7.4 (QGSJETII.04, Fluka, thinning $10^{-6}$)
- Calculate **total power** in 55 ns around peak emission
- **GEANT4** LORA simulation: total **deposited energy**
**Fit for each simulation**

Minimize $\chi^2$ of radio and particle data simultaneously

$$
\chi^2 = \sum_{\text{antennas}} \left( \frac{P_{\text{ant}} - f_r P_{\text{sim}}(x_{\text{ant}} + x_{\text{off}}, y_{\text{ant}} + y_{\text{off}})}{\sigma_{\text{ant}}} \right)^2 
+ \sum_{\text{detectors}} \left( \frac{d_{\text{det}} - f_p d_{\text{sim}}(x_{\text{det}} + x_{\text{off}}, y_{\text{det}} + y_{\text{off}})}{\sigma_{\text{det}}} \right)^2
$$

4 fit parameters:
- core position
- radio power scale factor
- particle density scale factor
10-90 MHz

zenith 31 deg
336 antennas
$\chi^2 / ndf = 1.02$

SB et al. PRD 90 082003 (2014).
zenith 55 deg
419 antennas
$\chi^2 / ndf = 1.1$

best fit out of 40 simulations
High band: Cherenkov rings

Harder to analyse due to tile beamforming

- First sample: 118 showers
- 200 - 450 antennas/event
- Fit 0.9 - 2.9
- Radiation mechanism finally completely understood!
$X_{\text{max}}$ reconstruction

*protons penetrate deeper than iron nuclei*

- Reconstruct depth of shower maximum: $X_{\text{max}}$
- Jitter: other variations in shower development
- Correction for atmospheric variations using GDAS
- Resolution $< 20 \text{ g/cm}^2$ !!

\[\chi^2 / \text{ndf} \]

\[X_{\text{max}} \text{ (g/cm}^2\text{)}\]
Mean $X_{\text{max}}$ for 118 showers

Mean statistical uncertainty per shower $\sim 17$ g/cm$^2$

Xmax syst. uncertainty $+14/-10$ g/cm$^2$

energy syst. uncertainty 27% (LORA)
Unbinned analysis

\[ a = \frac{\langle X_{\text{proton}} \rangle - X_{\text{shower}}}{\langle X_{\text{proton}} \rangle - \langle X_{\text{iron}} \rangle} \]

Calculate \( a \) for each individual shower
Composition at $10^{17} - 10^{18}$ eV

- LOFAR: high precision per event!
- Use **full** distribution of $X_{\text{max}}$ **not** only mean value
- First calculate mass parameter $a$
- Fit model distribution to measured distribution

$$a = \frac{\langle X_{\text{proton}} \rangle - X_{\text{shower}}}{\langle X_{\text{proton}} \rangle - \langle X_{\text{iron}} \rangle}$$
The composition of cosmic rays at 10^17 eV, just below the 'ankle', indicates that the mass composition of the cosmic rays should be dominated by a galactic component, even if the main galactic cosmic-ray population could be reaccelerated by the galactic-wind-termination shock or other processes.

Recent results from the Pierre Auger Observatory indicate that the abundances of individual elements depend on the hadronic interaction models. If the 'knee' in the all-particle cosmic-ray spectrum (a steepening at low energies) is caused by an extragalactic proton spectrum, then the main galactic cosmic-ray population, near 3 x 10^18 eV, could be the cause of the discrepancy in the fraction of iron near 3 x 10^18 eV (on the basis of figure 4 in ref. 8).

The spectral index for light elements changes to 30% at 3 x 10^18 eV, and has been measured with a mixture of protons and either helium (QGSJET.II04) or nitrogen (a hardening of the all-particle cosmic-ray spectrum), can be fitted with a two-component model that contains only proton and iron fractions. The optimal fit (largest value) is found for 0% helium fractions at all possible combinations, and solving for the nitrogen/helium fractions.

The cumulative probability density distribution for the parameter p (see equation (1)) determined from the data (blue line; best fit: 79% He, 19% N, 2% Fe) is shown in the figure. The uncertainty on these values is presented in table 1.

The composition of cosmic rays is allowed within systematic uncertainties has a statistical analysis, see Methods.
The composition of cosmic rays at 10 PeV would lie at an energy of at most 26 times larger. If the main galactic cosmic-ray population, then the corresponding iron ratio. A muon excess compared to all commonly used hadronic intermeasurements presented in ref. However, the light particle (p and He) fraction is found to be less than 30% at 3 PeV. However, the light-element (p and He) fraction is found to be less than 30% at 3 PeV. The spectral index for light elements changes to -1.5. As the energy decreases, the proton fraction of the composition that is allowed within systematic uncertainties has a value (see equation (1)) determined from the data (blue line; Fig. 2). The uncertainty on these values is presented in ref. 4, 342, 285 (2013). Alternatively, the original galactic shock such as the explosions of Wolf Rayet stars into their stellar winds may be the cause of the discrepancy in the fraction of light elements (p and He) lies between 0.38 and 0.98.

For information about the systematic uncertainties and source data, are available in the online paper. These sections appear only in the online paper. In that case, the 'ankle' in the cosmic-ray spectrum, at energies slightly greater than 10 PeV (on the basis of figure 4 in ref. 477–494 (2003)). A four-component model appears for a proton-dominated flux it is contrary to our data that appears for a proton-dominated flux. Instead, it can be explained as the imprint of pair production on the cosmic microwave background on neutrinos observed with IceCube.
Thunderstorm events

LOPES: Amplification in thunderstorms

LOFAR: strange polarisation features
Schellart et al. PRL 114, 165001 (2015)
Two layer model

h_2

shower axis

E_1

h_1

E_2

Schellart et al. PRL 114, 165001 (2015)
air shower particles ionize air

field enhancement at tips of hydrometeors

emerging streamer

Square Kilometre Array
Australia site 50-350 MHz
construction ~2020

~ 60,000 antennas in ~ 1 km²
SKA: ultrahigh precision measurements

LOFAR

SKA

Science:
- **origin of CRs**
  - mass composition in transition region G/XG
- **hadronic physics at super-LHC energies**
  - shower tomography
- **thunderstorm physics**

Huege et al. SKA science 2015 (arXiv:1408.5288)
Conclusions

• Air shower radio emission mechanism finally understood:
  - intensity profiles
  - wavefront shape
  - polarisation
  - Cherenkov rings at high frequency

• Radio method suitable for CR mass composition
  LOPES: proof-of-concept
  LOFAR: $X_{\text{max}}$ resolution of $< 20 \text{ g/cm}^2$
  similar to fluorescence detection + higher duty cycle

• Composition results based on 100+ high-res reconstructions
  using full shape of $X_{\text{max}}$ distribution
  light mass component at $10^{17} - 10^{17.5} \text{ eV}$

• Air showers in thunderstorm:
  remote sensing of electric fields, thunderstorm physics

• Future: ultra-high precision with SKA

Thanks