A study of radio frequency spectrum emitted by high energy air showers with LOFAR

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Cosmic ray radio emission

- Geomagnetic synchrotron emission

- Charge excess emission
  (Askarian effect)
  negative charge excess produced in the shower front
Cosmic ray radio emission

→ Geomagnetic synchrotron emission

→ Charge excess emission
  (Askarian effect)
  negative charge excess produced in the shower front

\[ v \times (v \times B) \]

\[ v \times B \]

\( v = \) shower axis
\( B = \) Earth magnetic field vector
Frequency spectrum study

- Is it possible to extrapolate information about primary particles by studying radio signals in the frequency domain?

- Set of simulated showers initiated by **PROTONS** and **IRON nuclei** (initial parameters: energy and arrival direction from real data)
Is it possible to extrapolate information about primary particles by studying radio signals in the frequency domain?

Set of simulated showers initiated by PROTONS and IRON nuclei (initial parameters: energy and arrival direction from real data)
Particle type: PROTON

Energy = $1.7 \cdot 10^{17}$ eV

$[\theta, \phi] = [45.25^\circ, 304.2^\circ]$
Frequency spectrum study: simulations

How does the frequency spectrum change as a function of distance to the shower axis and mass composition?

Particle types:
PROTON $\rightarrow X_{\text{max}} = 764.43 \text{ g/cm}^2$
IRON $\rightarrow X_{\text{max}} = 715.34 \text{ g/cm}^2$

Energy $= 1.7 \cdot 10^{17} \text{ eV}$
$[\theta, \phi] = [45.25^\circ, 304.2^\circ]$
Frequency spectrum study: simulations

→ $X_{\text{max}}$ increases with energy

→ for a fixed energy, $X_{\text{max}}(p) > X_{\text{max}}(\text{Fe})$

• Finding a variable which describes the frequency spectrum:
  → frequency of the 50th percentile
  → parameters of a fitted function
Comparison simulations – real data

Distribution of the 50th percentile frequency:
Background → simulations
Circles → antennas of LOFAR stations

Simulations INFO:
Energy = $1.7 \times 10^{17}$ eV
Arrival direction $[\theta, \varphi] = [45.25^\circ, 304.2^\circ]$

PROTONS → $X_{\text{max}} = 660.24 \text{ g/cm}^2$

Background → simulations
Circles → antennas of LOFAR stations

$X_{\text{max}} = 762.99 \text{ g/cm}^2$ (LDF fit)
Comparison simulations – real data

Distribution of the 50th percentile frequency:

- Background → simulations
- Circles → antennas of LOFAR stations

Simulations INFO:

- Energy = $1.7 \cdot 10^{17}$ eV
- Arrival direction $[\theta, \phi] = [45.25^\circ, 304.2^\circ]$

PROTONS → $X_{\text{max}} = 907.20 \text{ g/cm}^2$

Background → simulations

Circles → antennas of LOFAR stations

Distribution of the 50th percentile frequency:

- Frequency (MHz)
- Position in $\vec{v} \times \vec{B}$ direction (m)
- Frequency (MHz)
- Distance from shower axis (m)

$X_{\text{max}} = 762.99 \text{ g/cm}^2$ (LDF fit)
Comparison simulations – real data

Distribution of the 50th percentile frequency:

Background → simulations

Circles → antennas of LOFAR stations

Simulations INFO:

Energy = $1.7 \cdot 10^{17}$ eV

Arrival direction $[\theta, \phi] = [45.25^\circ, 304.2^\circ]$

PROTONS $\rightarrow X_{\text{max}} = 764.43 \text{ g/cm}^2$

X_{\text{max}} = 762.99 g/cm² (LDF fit)
Analysis on real data

Study the parameters of a fitted function

$$\log(\text{FFT}) = a + b \cdot \text{frequency}$$

Energy = $1.7 \cdot 10^{17}$ eV

Arrival direction $[\theta, \varphi] = [45.25^{\circ}, 304.2^{\circ}]$
Simulation study: $X_{\text{max}}$ dependence?

Distribution of the 50th percentile frequency (30 – 70 MHz) as function of $X_{\text{max}}$ for PROTONS at 200 m from the shower axis.
Simulation study: $X_{\text{max}}$ dependence?

Distribution of the 50th percentile frequency (30 – 70 MHz) as function of $X_{\text{max}}$ for PROTONS at 350 m from the shower axis.
Conclusions and outlook

- Study of the frequency spectrum on simulated events and real data

- the percentile method allows to find:
  - a strong dependence of the frequency spectrum as function of distance to the shower axis
  - a slight dependence on $X_{\text{max}}$

- **WORK in PROGRESS**:
  - analysis on simulations and real data by studying the fitted function of the FFT and comparison with results obtained by using the percentile method
Spare slides
Comparison simulations – real data

Distribution of the 50th percentile frequency:

Background → simulations

Circles → antennas of LOFAR stations

Simulations INFO:

Energy = $1.7 \cdot 10^{17}$ eV

Arrival direction $[\theta, \phi] = [45.25^\circ, 304.2^\circ]$

IRON → $X_{\text{max}} = 616.37 \text{ g/cm}^2$

$X_{\text{max}} = 762.99 \text{ g/cm}^2$ (LDF fit)
Comparison simulations – real data

Distribution of the 50th percentile frequency:
- Background → simulations
- Circles → antennas of LOFAR stations

Simulations INFO:
- Energy = $1.7 \cdot 10^{17}$ eV
- Arrival direction $[\theta, \phi] = [45.25^\circ, 304.2^\circ]$
- IRON → $X_{\text{max}} = 715.34 \text{ g/cm}^2$

Distribution of the 50th percentile frequency:
- Background → simulations
- Circles → antennas of LOFAR stations

Iron → $X_{\text{max}} = 762.99 \text{ g/cm}^2$ (LDF fit)
Spectrum of the signal of antenna 13 and its noise. Window = 128.