Precision radio detection of cosmic ray air showers

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LORA Scintillator

For the LOFAR Cosmic Ray KSP & Cosmic Lightning Project
Multiple emission mechanisms

# Geomagnetic:
- Electrons & positrons have transverse drift, induced by geomagnetic field.
- Linearly polarized, Unidirectional along v x B

# Charge excess:
- Negative charge buildup at shower front.
- Linearly polarized, Radially from shower axis

The full signal $E = E_G + E_C$ modified by
Time-compression effects.

Interpretation circular-polarization for fair weather

GeoMagnetic:

Charge eXcess:

ChX Peaks lower in atmosphere than GM (physics)
At 100 m, 30-80 MHz, delay = 1 ns

\[ I = \frac{1}{n} \sum_{0}^{n-1} \left( |\mathcal{E}_{i,\vec{v} \times \vec{B}}|^2 + |\mathcal{E}_{i,\vec{B} \times \vec{v}}|^2 \right) \]

\[ Q = \frac{1}{n} \sum_{0}^{n-1} \left( |\mathcal{E}_{i,\vec{v} \times \vec{B}}|^2 - |\mathcal{E}_{i,\vec{B} \times \vec{v}}|^2 \right) \]

\[ U + iV = \frac{2}{n} \sum_{0}^{n-1} \left( \mathcal{E}_{i,\vec{v} \times \vec{B}} \mathcal{E}_{i,\vec{B} \times \vec{v}}^* \right). \]

Stokes parameter V is measure of circular polarization

Slight delay between GM & ChX causes rotation in polarization
Transverse current is 1 ns ahead of Charge excess pulse (@ 100 m, 30-80 MHz)

Conclusion:

even the very subtle circular polarization is well understood & accurately measured at LOFAR
Observations; polarization footprint

Fair weather vs thunderstorm

P. Schellart et al. (PRL 114, 165001)
Fair weather vs thunderstorm

Observations; intensity footprint

S. Buitink et al., PRD 90, 082003 (2014)

P. Schellart et al., PRL 114, 165001 (2015)
A fair-weather event

Observations; circular polarization

Fair weather vs thunderstorm

$v \times (v \times B)$
Physics for thunderstorm events

Atmospheric fields induce electric currents in shower plasma

Like for Fair Weather:
Circular polarization due to emission-height differences.

Here: caused by height dependence of orientation of atmospheric fields.

Independent of observer position.
Atmospheric electric fields

Challenge: Many parameters $\rightarrow$ grid search cumbersome
Levenberg-Marquardt minimization requires: Fast & Deterministic code
Semi-analytic approximation developed
A reconstructed thunderstorm event

Intensity

Linear polarization direction

Circular

T.N.G. Trinh et al. (PRD 95, 083004 (2017))

<table>
<thead>
<tr>
<th>Layer</th>
<th>1</th>
<th>2</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Height (km)</td>
<td>8–5</td>
<td>5–2</td>
<td>2–0</td>
</tr>
<tr>
<td>$</td>
<td>E_\perp</td>
<td>\ (kV/m)$</td>
<td>50</td>
</tr>
<tr>
<td>$\alpha (^\circ)$</td>
<td>98</td>
<td>98</td>
<td>8</td>
</tr>
<tr>
<td>$E_{vxy}$ (kV/m)</td>
<td>46</td>
<td>13</td>
<td>4</td>
</tr>
<tr>
<td>$E_{vyx\perp}$ (kV/m)</td>
<td>-22</td>
<td>-9</td>
<td>8</td>
</tr>
</tbody>
</table>
Conclusions

Radio emission from air showers is very well understood
Radio emission from air showers is accurately measured at LOFAR
example of both: circular polarization for fair weather

Thus:
Radio-detection of air showers can be used as diagnostic tool
- X-max
- atmospheric electric fields
Uniqueness of the results
Analytic code vs CoREAS

Circular polarization distinguishes $E_3$ to left or to right
Full polarization, Stokes

Stokes parameters: $I$, $Q$, $U$, $V$
Linear polarization angle: $2 \varphi = \text{atan}(U/Q)$
Circular polarization = $V/I$

Interesting results:

- **Fair weather:**
  confirmation of emission mechanisms
- **Thunderstorm:**
  Finite circular pol. near core due to changing atmospheric E-field