Implications for the Radio Detection of Cosmic Rays

–from–

Accelerator Measurements of Particle Showers in a Magnetic Field

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Radio Emission of Cosmic Ray Air Showers

- Two main emission mechanisms:
  - Geomagnetic emission: separation of positive and negative charges in shower due to Lorentz force:
    \[ \overrightarrow{E} \propto \overrightarrow{v} \times \overrightarrow{B} \]
  - Askaryan emission: radiation from net negative charge excess in shower

- Broadband (MHz – GHz)
- Cherenkov-like emission pattern
  - Coherent up to cutoff frequency
The RF Technique: A Maturing One

- Dominated by Geomagnetic, but some Askaryan
  \[PAO \text{ Collab. Phys Rev. D. 2014}\]

- Electromagnetic models + hadronic shower codes predict magnitude of E-field
  \[\text{Recently shown to be consistent with LOPES measurements at 16\% level}\]
  \[Apel \text{ et al. Astropart. Phys. 2016}\]

- Beam pattern depends on shower geometry, observation frequencies, atmosphere index of refraction \(n\)
  \[Nelles \text{ et al. Astropart. Phys. 2015}\]
  \[de \text{ Vries, et al. PRL 2011}\]
THE RF TECHNIQUE: A MATURING ONE

- Dominated by Geomagnetic, but some Askaryan

- Electromagnetic models help calculate the induced E-field to predict magnitude

- Recently shown to be consistent with LOPES measurements at 16\% level

- Beam pattern depends on shower geometry, observation frequencies, atmosphere index of refraction $n$
  \textit{Nelles et al. Astropart. Phys. 2015}
  \textit{de Vries, et al. PRL 2011}

Beam test calibrates RF models in a different system.
IMPORTANT FOR e.g. ANITA

➤ UHECRs observed by ANITA at high frequencies 2006/2007
   ➤ Inconsistent with models at the time PRL 105, 2010
      ➤ Predicted no observable power in the ANITA band
   ➤ Current models allow for this if include realistic $n$

➤ Energy of ANITA UHECRs
   ➤ ANITA samples RF emission at a single point
   ➤ RF beam width degenerate with CR energy

Schoorlemmer et al, 2016
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Schoorlemmer et al, 2016
THE NEED TO GO TO AN ACCELERATOR

➤ Test emission mechanism in a controlled laboratory environment:
  ➤ Relative strength of Askaryan to Geomagnetic
  ➤ Do the RF models accurately predict the absolute magnitude of E-field?
  ➤ Does coherence depend on the index of refraction?
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**Challenge:** Build a laboratory scale model of a km-scale air shower
Currents Paradigm

Askaryan Radiation:
net (negative) charge excess in the shower

\[ A_{\text{Askaryan}} \sim J_{||} \]
CURRENTS PARADIGM

Askaryan Radiation: net (negative) charge excess in the shower
\[ A_{Askaryan} \sim J_{||} \]

Geomagnetic Radiation: charge separation in the presence of a magnetic field
\[ A_{Geomagnetic} \sim J_{\perp} \]

Kahn, Lerche, 1976
Scholten, Werner, Rushydi, 2008
Both currents scale with the total track length, $L$, of the shower.

Shower length shorter in dense media, so: $L_{||} \sim \frac{1}{\rho}$

Instantaneous Transverse current scales with transverse drift velocity: $v_d \sim a_{\perp} t \sim \frac{B}{\rho}$

Geomagnetic : Askarayn

$$\frac{J_\perp}{J_{||}} \sim \frac{B}{\rho}$$
Both currents scale with the total track length, $L$, of the shower.

Shower length shorter in dense media, so: $L_{||} \sim \frac{1}{\rho}$

Instantaneous Transverse current scales with transverse drift velocity: $v_d \sim a_\perp t \sim \frac{B}{\rho}$

Scaling shower length down by a factor of 1000, requires $O(1 \text{ kG})$ magnetic field in the lab!
SLAC T-510 Objectives

➤ Design Principles
   ➤ Scale magnetic field & bandwidth to the lab
   ➤ Isolate electromagnetic emission from hadronic physics
   ➤ Separate Askarayan emission from Magnetic Emission

➤ Complement Air Shower Measurements with Lab Exp.
   ➤ Controlled electromagnetic showers with precise geometry
   ➤ Controllable magnetic field → Controllable Magnetic Emission
   ➤ Map out beam patterns → Test of Cherenkov cone, importance of $n$
**Askaryan Radiation in the Lab**

Similar to previous measurements of Askaryan:

Saltzberg et al PRL 2001
Gorham et al PRL 2007

4.35, 4.55 GeV electron beam,
131 nC per bunch

High Density Polyethylene
Target, $n \approx 1.53$

RF Absorber

Radio Cherenkov emission

Antennas:
- 30-300 MHz
- 300-1200 MHz
- 3-18 GHz

1.4-12.4 m
MAGNETIC RADIATION IN THE LAB

Antennas:
- 30-300 MHz
- 300-1200 MHz
- 3-18 GHz

4.35, 4.55 GeV electron beam, 131 nC per bunch

High Density Polyethylene Target, n~1.53

RF Absorber

Radio Cherenkov emission

Uniform B-Field, \( \leq 1000 \) Gauss

4 m
**IN PRACTICE: LABORATORY SETUP**

- End Station A in End Station Test Beam at SLAC

300-1200 MHz antennas
scales to 10-60 MHz in air showers
BEAM CHARACTERISTICS

- 4.35, 4.55 GeV electron beam
- $131 \pm 3$ pC average bunch charge
- Equivalent to $4 \times 10^{18}$ eV cosmic ray primary
Magnetic Field

- 15 water-cooled stacked solenoids
- Vertical magnetic field $\leq 970$ G
Air Shower Simulations Adapted for T-510

- Radio-frequency emission codes based on track-level calculations of RF emission used in extensive air shower simulations.

- Formalisms:
  - ZHS used in ZHSAires
  - Endpoints used in CoREAS
  - Particle showers simulated with GEANT4
**Track-Level Model Details**

- Divide particle trajectories up into tracks, sum the radiation for all tracks
- RF emission calculated from first principles, with no free parameters
- Includes:
  - Full measured magnetic field model
  - Refraction
  - Fresnel transmission
  - De-magnification effects
  - Transition Radiation estimated with Endpoints $\rightarrow 1\%$ percent
Signal Polarization

- Particle Shower
- Magnetic Field
- Shower Axis
- Coordinate System
- Cherenkov Cone

- Askaryan radiation (radially oriented)
- Geomagnetic radiation (oriented normal to shower axis and magnetic field direction)
SIMULATED EMISSION: NO MAGNETIC FIELD

\[
\begin{align*}
\text{Electric Field (V/m)} & \\
\text{Antenna Position on Vertical Axis (m)} & \\
& 2 \quad 3 \quad 4 \quad 5 \quad 6 \quad 7 \quad 8 \quad 9 \quad 10
\end{align*}
\]

\[
\begin{align*}
\text{Antenna Position on Horizontal Axis (m)} & \\
& -6 \quad -4 \quad -2 \quad 0 \quad 2 \quad 4 \quad 6
\end{align*}
\]

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\]

\[
\begin{align*}
\text{Hpol} & \\
\text{Vpol}
\end{align*}
\]

\[T-510\ \text{Collab. in prep, 2016, A. Zilles, ICRC 2015}\]
**SIMULATED EMISSION: FULL B-FIELD**

\[ H_{pol} \quad V_{pol} \]

**Electric Field (V/m)**

**Antenna Position on Vertical Axis (m)**

**Antenna Position on Horizontal Axis (m)**

*T-510 Collab. in prep, 2016, A. Zilles, ICRC 2015*
Separating components* by design

* In practice: compare full simulations to measurements
On the Cherenkov Cone

- ZHS & Endpoints agree within 7% over 300-1200 MHz spectral band
- Reflections (~1ns, 6ns) evident in measured spectra and waveforms → 40% systematic uncertainty
- Disagreement in peak amplitude between data and simulations is 35%
**Scaling with Magnetic Field Strength**

- **$V_{pol}$** constant with increased $B$
- $H/V$ scales linearly with $B$

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Linearity confirms currents paradigm!

**Sign reversal when flipping direction of magnetic field**

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**Figure (a)**

- $H/V$ Peak Voltage Ratio
- $B = 0.97$ kG
- $B = 0.73$ kG
- $B = 0.49$ kG
- $B = 0.24$ kG

**Figure (b)**

- Sign reversal when flipping direction of magnetic field

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**Legend**

- **ZHS**
- **Endpoints**
- **Data**
- **Fit**
Magnetic emission forms a Cherenkov cone!
Comparison to Air Shower Experiments

<table>
<thead>
<tr>
<th>Experiment</th>
<th>δf (MHz)</th>
<th>θ&lt;sub&gt;c&lt;/sub&gt;</th>
<th>δθ</th>
<th>δθ &gt; θ&lt;sub&gt;c&lt;/sub&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>LOPES</td>
<td>43-74</td>
<td>1°</td>
<td>2°</td>
<td>→ Filled in Cherenkov cone</td>
</tr>
<tr>
<td>LOFAR</td>
<td>110-190</td>
<td>1°</td>
<td>&lt;1°</td>
<td></td>
</tr>
<tr>
<td>ANITA</td>
<td>200-1200</td>
<td>1°</td>
<td>&lt;1°</td>
<td>δθ &lt; θ&lt;sub&gt;c&lt;/sub&gt;</td>
</tr>
<tr>
<td>T-510</td>
<td>300-1200 / 10-60</td>
<td>49°</td>
<td>5°</td>
<td>→ Cherenkov annulus</td>
</tr>
</tbody>
</table>
CONCLUSIONS ABOUT THE T-510 EXPERIMENT

- First laboratory experiment of RF emission from particle showers in magnetic field
- Complements cosmic-ray air showers observations:
  - Different systematics
  - Insensitive to hadronic physics & uncertain shower geometries
- Agreement between first principles RF models and accelerator data to within systematic uncertainty
- Hpol Scaling with magnetic field + RF Component separation confirms current paradigm
- Observed Cherenkov cone emphasizes importance of certain details (e.g., index of refraction)