Particle Astrophysics at Zettavolt Energies with Radio Detectors in Low Lunar Orbit

Andres Romero-Wolf
Jet Propulsion Laboratory, California Institute of Technology
April 17, 2021
Zettavolt Askaryan Polarimeter

Opening a new window into the extreme energy universe

Astrophysical sources accelerate particles to extreme energies.

Cosmic rays interact in the lunar regolith

Atomic nuclei deflected by Galactic magnetic fields

A radio detector in low lunar orbit achieves unprecedented sensitivity to the highest energy cosmic rays.

Andrés Romero-Wolf\textsuperscript{a}, Jaime Alvarez-Muñiz\textsuperscript{b}, Luis A. Anchordoqui\textsuperscript{c}, Douglas Bergman\textsuperscript{d}, Washington Carvalho Jr.\textsuperscript{e}, Austin L. Cummings\textsuperscript{f}, Peter Gorham\textsuperscript{g}, Casey J. Handmer\textsuperscript{a}, Nate Harvey\textsuperscript{a}, John Krizmanic\textsuperscript{h,k}, Kurtis Nishimura\textsuperscript{i}, Remy Prechelt\textsuperscript{g}, Mary Hall Reno\textsuperscript{j}, Harm Schoorlemmer\textsuperscript{k}, Gary Varner\textsuperscript{g}, Tonia Venters\textsuperscript{k}, Stephanie Wissel\textsuperscript{l}, Enrique Zas\textsuperscript{b}

\textsuperscript{a}Jet Propulsion Laboratory, California Institute of Technology, \textsuperscript{b}IGFAE & Universidade Santiago de Compostela, \textsuperscript{c}Lehman College, City University of New York, \textsuperscript{d}University of Utah, \textsuperscript{e}Universidade do São Paulo, \textsuperscript{f}Gran Sasso Science Institute, \textsuperscript{g}University of Hawai‘i at Manoa, \textsuperscript{h}University of Maryland, \textsuperscript{i}University of Iowa, \textsuperscript{j}Max Planck Institute, \textsuperscript{k}NASA Goddard Space Flight Center, \textsuperscript{l}Pennsylvania State University,
Low Radio Frequencies Provide Access to Higher Energies

- Frequencies < 300 MHz have wide radio beams with a large range of view angles producing a detectable signal at ultra-high energies.

- Frequencies > 300 MHz are narrowly beamed with a small range of view angles producing a detectable signal.
ZAP - prospects

Antenna array in lunar orbit operating for 2 years can increase the statistics by an order of magnitude with full sky coverage.
ZAP Science – acceleration mechanisms

• Interactions of UHE cosmic rays with photon background (e.g. radio, microwave, IR, optical) result in energy loss during propagation.
• Auger and TA show a clear suppression (20σ significance).
• Increasing mass composition with increasing energy can mean one of two things:
  • Rigidity-dependent maximum energy of nearby sources is limited (running out of steam).
  • Heavier elements are suppressed due to photon fields at the source while lighter elements are not.
    • $E_{\text{max}} \propto Z$
    • $\frac{dE}{dx} \propto A$
• Prediction is that the subdominant proton spectrum is recovered for $E>10^{20.2} \text{ eV}$. 

\[
\frac{\Delta E}{E} = 30\% \\
\text{Proton fraction 20%}
\]
ZAP Science – composition at the highest energies

- ZAP is not sensitive to $X_{\text{max}}$ (nuclear composition).
- However, it can test for clustering of hot spots as a function of energy.
- Composition is expected to get heavier with increasing energy.
- Clustering of hotspots as a function of energy could identify clusters could reveal sources of light particles at ultra-high energies expected from energy cutoffs due to photon field.
- This finding would be important for prospects of neutrino astronomy at ultra-high energies.

Scattering due to Galactic magnetic field deflections

$$\theta \sim 1^\circ Z \left( \frac{E}{100 \text{ EeV}} \right)^{-1}$$

Adapted from Anchordoqui et al. 2020
ZAP Science – full sky anisotropy studies

- Independent identification the sources of the highest energy cosmic rays and test the mechanism by which the spectrum cuts off.
- Full sky coverage with \( \geq 1000 \) events with \( E \geq 10^{19.6} \) eV

<table>
<thead>
<tr>
<th>Parameter</th>
<th>( f_{\text{sig}} )</th>
<th>( \theta )</th>
<th>AGN</th>
<th>SBG</th>
<th>2MRS</th>
</tr>
</thead>
<tbody>
<tr>
<td>10%</td>
<td>20°, 15°</td>
<td>1240</td>
<td>2,060</td>
<td>1,910</td>
<td>( &gt;5,000 )</td>
</tr>
<tr>
<td></td>
<td>15°</td>
<td>920</td>
<td>1,910</td>
<td></td>
<td>4,830</td>
</tr>
<tr>
<td>15%</td>
<td>20°, 15°</td>
<td>680</td>
<td>1,000</td>
<td>870</td>
<td>2,250</td>
</tr>
<tr>
<td></td>
<td>15°</td>
<td>660</td>
<td></td>
<td></td>
<td>2,280</td>
</tr>
<tr>
<td>20%</td>
<td>20°, 15°</td>
<td>&lt;650</td>
<td>&lt;650</td>
<td>&lt;650</td>
<td>1,520</td>
</tr>
<tr>
<td></td>
<td>15°</td>
<td>&lt;650</td>
<td>&lt;650</td>
<td></td>
<td>1,320</td>
</tr>
</tbody>
</table>
ZAP Science – Channels for detection of superheavy dark matter

SHDM identified >ZeV $\nu$’s and $\gamma$’s and directionally correlated with local DM distribution.

Purely electromagnetic showers can be identified via the LPM effect.

Expected to provide order of magnitude improvements in SHDM constraints.

Image credit: new scientist
Detector Concept

SmallSat array of short dipoles (~ 1m)

Top View

1 m

ESPAring

Side View

6 m

6 m

Dipole

Boom

BEACON short dipoles demonstrated Galactic noise limited sensitivity 30 – 80 MHz band.

Sky noise-limited sensitivity of 1 m dipole with impedance transformer.

ANITA heritage of low power digitizers and triggering electronics.

Image credit: E. Oberla

Image credit: ANITA Collaboration
ZAP - Event Reconstruction

Pointing resolution $\sim 10^\circ$ is achievable
It is possible to drive it down further with more channels.

<table>
<thead>
<tr>
<th>Contribution</th>
<th>Allocation</th>
<th>Depends on…</th>
<th>Controlling parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>RF Pointing</td>
<td>3°</td>
<td>• Antenna separation.</td>
<td>• Antenna separation</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Signal strength.</td>
<td>• Sensitivity</td>
</tr>
<tr>
<td>Lunar topography</td>
<td>2 – 8°</td>
<td>• RF pointing</td>
<td>• RF pointing (TBD)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Lunar region</td>
<td></td>
</tr>
<tr>
<td>In-plane CR tilt angle</td>
<td>5°</td>
<td>• Askaryan signal spectrum</td>
<td>• RF Sensitivity</td>
</tr>
<tr>
<td>Out of plane CR tilt angle</td>
<td>8°</td>
<td>• Polarization</td>
<td>• RF Sensitivity</td>
</tr>
</tbody>
</table>

Reconstruction will require 3 or 4 antennas in each polarization (9-12 dipoles total).
Baseline separation $> 5$m needed.

RF Pointing by beamforming

Lunar Topography

Polarization angle resolution

$$\delta \theta \approx \frac{1}{SNR}$$
Planetary Science Application: Detecting Ice in the Permanently Shadowed Regions of Airless Bodies

- Evidence of relatively pure extensive ice deposits in Mercury’s Permanently Shadowed Regions (PSRs).
- Only traces of water ice have been found on the surface of lunar PSRs.
- The Moon could host extensive ice deposits at > 1 m depths.
- UHECRs illuminate subsurface ice!
Planetary Science Application: Detecting Ice in the Permanently Shadowed Regions of Airless Bodies

- Evidence of relatively pure extensive ice deposits in Mercury’s Permanently Shadowed Regions (PSRs).
- Only traces of water ice have been found on the surface of lunar PSRs.
- The Moon could host extensive ice deposits at > 1 m depths.
- UHECRs illuminate subsurface ice!

Image credit: P. Gorham w/ Remcom XFDTD
Outlook and Conclusions

• Lunar detector concept under development.
  • Event clustering simulations at the highest energies.
  • Particle and radio emission propagation models for the Moon.
  • Development of ultra-wide band electrically short dipole.
  • Sensitivity to extensive ice deposits.

• Initial estimates of a low-frequency antenna array in lunar orbit show promising prospects for extremely high energy particles not available to ground arrays.

• ZAP offers a low cost way to search for extensive ice deposits in the permanently shadowed regions of airless bodies.