Radio Detection of GZK Neutrinos: Potential for Balloon-borne and Underground Salt-dome detectors

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*NeSS 2002*
Particle astrophysics at the highest energies

- Universe optically thick to photons above ~10 TeV
- Protons probably extragalactic above 10 EeV, but cannot propagate more than a few tens of Mpc \( \rightarrow \) GZK cutoff
- Astronomy above ~10 TeV can only be done with neutrinos
- GZK process itself is a source; Maybe the ONLY source \( \rightarrow \) Design for GZK flux!
What role does radio detection play?

- Standard model GZK ν rate:
  - ~0.2 per km$^3$ w.e. per year over $2\pi$ sr
- Cf. Engel, Seckel, & Stanev 2001

<table>
<thead>
<tr>
<th>Log$L_{\nu\bar{\nu}}$ (GeV)</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
</tr>
</thead>
<tbody>
<tr>
<td>All $\nu$, NC</td>
<td>0.052</td>
<td>0.046</td>
<td>0.032</td>
<td>0.008</td>
<td>0.001</td>
</tr>
<tr>
<td>$\nu_e$, CC</td>
<td>0.054</td>
<td>0.051</td>
<td>0.046</td>
<td>0.024</td>
<td>0.004</td>
</tr>
<tr>
<td>$\nu_{\mu} + \nu_{\tau}$, CC</td>
<td>0.092</td>
<td>0.080</td>
<td>0.057</td>
<td>0.014</td>
<td>0.002</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>0.192</td>
<td>0.177</td>
<td>0.144</td>
<td>0.046</td>
<td>0.007</td>
</tr>
</tbody>
</table>

- Need ~1000 km$^3$ sr to get 30 events per year: A Teraton detector

- A possible solution: Askaryan process: coherent radio Cherenkov emission

  - EM cascades $\Rightarrow$ net charge asymmetry $\Rightarrow$ radio pulse
  - Process is coherent $\Rightarrow$ Quadratic rise of power with cascade energy
  - Neutrinos can shower in radio-transparent media: ice, rock salt, etc.

- **RF economy of scale very competitive for giant detectors**

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Askaryan process: Radio Cherenkov

Calorimetric

Vector directionality

SLAC T444, Saltzberg et al. PRL 2001

SLAC T460, Gorham et al. 2002

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Askaryan process: Radio Cherenkov (II)

Huge dynamic range, linearity

SNR dominant at $E > 10$ PeV
Exploiting the Askaryan effect

- Other experiments: Radio Ice Cherenkov Experiment (RICE) (D. Seckel talk), Goldstone Lunar Ultra-high energy neutrino Experiment (GLUE)

Potential GZK $\nu$ Detectors:
- Antarctic Impulsive Transient Antenna (ANITA) (cf. Gorham or K. Liewer, Kona SPIE 2002)
  - Balloon-borne VHF-UHF antenna array: view ~1M km$^3$ of ice sheet
  - NASA Space research & technology (SR&T) mission, 2005-2006 launch
  - Coarse angular & energy precision but very high potential sensitivity
  - Expect $\sim2000$ km$^3$ sr aperture at $\sim1$ EeV
  - Long duration balloon=30 days/yr, Ultra-long duration balloon=100days/yr

- Saltdome Shower Array (SALSA) (cf. D. Saltzberg Kona SPIE 2002)
  - Antenna array(s) embedded in saltdome(s)
  - Concept: 10 by 10 strings, 10 antenna nodes per string, $\sim250$ m spacing
  - $2\pi$ sr (no muons!) available, density 2.2 $\Rightarrow$ $\sim400$ km$^3$ sr at 1 EeV
Antarctic Impulsive Transient Antenna (ANITA)

- **ANITA Goal:** Pathfinding mission for GZK
- NASA SR&T start October, launch in `05-`06
- UH (Gorham, Learned, Varner), UCI (Barwick), JPL (Liewer, Naudet), Penn State (Beatty, Coutu, Cowen), U.Del. (Seckel, Evenson, Clem), UCLA (Saltzberg), U.Minn. (DuVernois), UW (Halzen), Utah (Kieda), Kansas (Besson)

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ANITA Payload

Simulated pulse—multiple antennas

- ANITA antennas view ~2π sr with 60 deg overlapping beams
- Beam intensity gradiometry, interferometry, polarimetry used to determine pulse direction & thus original neutrino track orientation

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Antarctic ice topography

- RadarSat completed comprehensive SAR map of Antarctica in late 1990s—feature resolutions of ~10-50m, available public domain
- Can calibrate surface roughness—SAR $\lambda = 5.6$ cm
ANITA questions & issues

• RF interference?
  – Studies suggest Antarctica is extremely quiet

• How will cascade pulses be distinguished?
  – Askaryan pulse spectrum: unique bandwidth, coherence, polarization

• Energy & Angular resolution?
  • Pulse interferometry & beam gradiometry $\Rightarrow ~5-10^0$
  • Depth of cascade from spectral rolloff & known ice properties
  • Track angle from plane of polarization
  • $\Delta E/E \sim 1$ from combination of all of the above
Natural Salt Domes: Potential PeV-EeV Neutrino Detectors

- Rock salt can have extremely low RF loss: as radio clear as Antarctic ice
- ~2.4 times as dense as ice
- typical salt dome: 50-100 km$^3$ water equivalent in top ~3km

Salt domes: found throughout the world…

Qeshm Island, Hormuz strait, Iran, 7km diameter salt dome

Caprock visible from space

Isacksen salt dome, Elf Ringnes Island, Canada  8 by 5km
Saltdome Shower Array: SALSA

Halite (rock salt)
- $L_\alpha(<1\text{GHz}) > 500 \text{ m w.e.}$
- Depth to $>10\text{km}$
- Diameter: 3-8 km
- $V_{\text{eff}} \sim 100-200 \text{ km}^3 \text{ w.e.}$
- No known background
- $>2\pi$ steradians possible
Results from Hockley Mine rock salt tests

- All results consistent with >200 meter attenuation lengths
- Supported by ground-penetrating radar results since early 1970’s
  - Radar pulses sent through ~3 km of salt in some Gulf-coast salt domes

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US Gulf Coast Saltdomes

Salt dome demographics:

- Several hundred known in Gulf coast area alone—some are good source of oil

- Mapped for oil (on flanks, not in salt) but most are undeveloped
Roadmap to a large-scale salt detector

1. Verify Askaryan process: silica sand, SLAC T444, 2000
2. Identify radio-transparent natural salt structures 2001
   • GPR tests from 1970’s give strong indications
   • Hockley salt dome tests (Gorham et al. 2002) confirm La>250m
3. Extend accelerator results to rock salt: 2002
   – SLAC T460: salt behaves as predicted!
4. Cosmic-ray testbed for antenna development/signal characterization 2002
   • In progress at Univ. of Hawaii progress since early August
5. Deploy an on site testbed in a salt mine 2003-2004
   • Small antenna array—study backgrounds
7. Detector construction & deployment 2007-2010
Existing Neutrino Limits and Potential Future Sensitivity

- RICE, AGASA, Fly’s Eye limits for $\nu_e$ only
- GLUE limits $\nu_\mu$ & $\nu_e$  
  - ~80 hours livetime
- FORTE limits $\nu_\mu$ & $\nu_e$  
  - 3.8 days live, Greenland ice

- SALSA & ANITA sensitivity:  
  - Based on 2 independent Monte Carlo simulations: D. Saltzberg (SPIE02), Gorham (GLUE adaptation); $\nu_\mu$ & $\nu_e$ included, full-mixing not yet

Models:
- Topological Defects: Sigl; Protheroe et al.; Yoshida et al.
- AGN: Protheroe et al.; Mannheim
- GZK neutrinos: Engel et al. ‘01
Summary

Radio Detection:
The Dark horse in the GZK neutrino race…

• ANITA appears to have the earliest shot at constraints (or detection) of the GZK flux (2005-2006 austral summer)

• SALSA: probably the most cost-effective GZK neutrino telescope