Progress Towards Radio and Acoustic Detection of Ultra High Energy Neutrinos

A tale of salt mines, particle accelerators and balloon flights---from the South Pole to the Moon, from the deep ocean to low-Earth orbit.

David Saltzberg
University of California, Los Angeles
Nobel Symposium #129
August 21, 2004
Astrophysical Neutrino Sources
“Batting 1000”

Every source has:
1. has had major impact on particle physics
2. Looks deeper into the source than otherwise possible

\[ \nu \text{ weak eigenstates} \neq \text{mass eigenstates} \]

\[ \nu \text{ mass} \]

dispersion\(\rightarrow\)\(\nu\) mass limits
The range of photon astronomy

Radio Astronomy
$<10^{-7}$ eV photons

Atmospheric Cherenkov
$>10^{12}$ eV photons

...and everything in between
The end of photon astronomy

- No Extra-galactic photon astronomy beyond $\sim 10^{14}$ eV

No cutoffs for neutrinos
Beyond $10^{14}$ eV?

Astrophysical processes are producing particles over at least 7 more orders of magnitude.

Sources are still a mystery:

AGN, GRBs?

Neutrinos would point back:

- Sources may produce neutrinos directly
- or indirectly ("GZK process")

\[ p + \gamma_{2.7K} \rightarrow \Delta^* \rightarrow n + \pi^\pm \]

\[ \rightarrow \mu\nu \]

\[ \rightarrow e\nu\nu \]

“guaranteed” neutrinos

from S. Swordy
A Motivation for a Particle Physicist

- **Exotic Physics**: UHECR would result from decays of super-heavy particles.
- **Example**: Grand Unified Supersymmetric Theories:

\[ M_X \sim 10^{25} \text{ eV} \]

Is its lifetime comparable to age of universe or is it \( \sim 10^{-40} \) sec?
Loophole—produce them continuously by “topological defects” remaining from Big Bang
Summary UHE ν Models

Intensity \( (I) \) = \( \frac{d^3N}{dA d\Omega dt} \)

Brightness \( (I_E) \) = \( \frac{d^4N}{dA d\Omega dt dE} \)

• Possible point of confusion:
  - Models give brightness
  - But, experiments measure intensity

from P. Gorham
Neutrino interactions

Most commonly used: Ghandhi et al., Astropart. Phys. 5, 81 (1996):

- Low-x: (~10^{-8}) even SM UHE neutrino cross sections are controversial
  - e.g. above 10^{17} eV, more likely to scatter off of bottom sea, than u,d valence
Particle Physics with the UHE Neutrino Cross Section

- Cross section can be measured by looking at zenith angle distributions
- Not accessible by LHC; UHECR not useful
Quantifying Detection

- \([A \Delta \Omega] \Delta t\) vs. energy (& background) for each neutrino flavor describes experiment

\[ N_{obs} = \int I_E \times [A \Delta \Omega] dA d\Omega dE dt \]

- For example: \([A \Delta \Omega]\) for a flat, black paddle = \(A \times 2\pi\)
- \([V \Delta \Omega] = [A \Delta \Omega] \times L_{int}\) accounting for neutrino cross section vs. energy
- (Discovery potential also depends on background)

- Need many \(\text{km}^3\) of material to detect > \(10^{15}\) eV

- Here I’ll give (my estimates of):
  - \(E_{\nu}^{\text{thresh}}\) (approx.)
  - typical \([V \Delta \Omega]\) and \(\Delta t\)
  - Compare at the end with \([A \Delta \Omega] \Delta t\) for detection
UHE event will induce an $e/\gamma$ shower:

In electron-gamma shower in matter, there will be $\sim 20\%$ more electrons than positrons.

Compton scattering: \[ \gamma + e^-_{(at \ rest)} \rightarrow \gamma + e^- \]

Positron annihilation: \[ e^+ + e^-_{(at \ rest)} \rightarrow \gamma + \gamma \]
Excess charge moving faster than\( c/n \) in matter emit Cherenkov Radiation

\[
\frac{dP_{CR}}{d\nu} \propto \nu d\nu
\]

Each charge emits field \(|E| \propto e^{i k \cdot r}\)
and Power \( \propto |E_{\text{tot}}|^2 \)

In dense material \( R_{\text{Moliere}} \sim 10\text{cm}. \)

\( \lambda << R_{\text{Moliere}} \) (optical case), random phases \( \Rightarrow P \propto N \)

\( \lambda >> R_{\text{Moliere}} \) (microwaves), coherent \( \Rightarrow P \propto N^2 \)

Confirmed with Modern simulations + Maxwell’s equations:

(Halzen, Zas, Stanev, Alvarez-Muniz, Seckel, Razzaque, Buniy, Ralston, McKay …)
The SLAC "Kitty Litter" box

4 tons SiO$_2$

- Amplitude expected
- 100% linearly polarized
- Cherenkov angle
RICE Experiment

- “Radio in Ice Experiment”
- Dipoles (100-1000 MHz) on AMANDA strings @ South Pole
- 200 x 200 x 200 meter array
- Uses long attenuation length (~7km)
- $E_\nu > \sim 10^{17}$ eV
- $[V\Delta\Omega] \sim 10 \text{ km}^3\text{-sr}$
- Status
  - published on 3-year dataset
  - datataking ongoing
- Expected events in 5 years:
  - ~9 TD events
  - 2-7 GZK events
  - ~3 GRB/AGN events

South Pole Ice properties: RF propagation

- Tried to measure attenuation from far hole in 2003-04 season
- Refraction Made it difficult to transmit from a far hole to the RICE array
- Radioglaciology proposal pending with NSF
South Pole Ice properties:
RF attenuation

- Deeper ice is, on average, even colder – So will have an even longer attenuation length

Radio Echo measurements
Amundsen–Scott Station
S. Barwick et al. 2004

Average attenuation to 1200m depth
mean T = -45°C
Errorbars show ~2σ systematics
Using the Moon as a 200,000 km$^3$ target

- Zheleznyk and Dagkesamanskii (1988)
  - $10^{20}$ eV $\nu$ produces $\sim 1000$ Jy at 2GHz
    
    $(1\text{Jy} = 10^{-26} \text{W/m}^2/\text{Hz})$
  - brightest quasars $\sim 25$ Jy at this frequency band
  - Moon as blackbody: $\sim 200$ Jy
    - no need to go to the moon
    - use radiotelescopes

First results (1996)
12 hrs using single Parkes 64m dish in Australia.

Lmittted by R.F.I.

Goldstone Lunar UHE Neutrino Search (GLUE)

P. Gorham et al., PRL 93, 041101 (2004)

Two antennas at JPL’s Goldstone, Calif. Tracking Station

- limits on $>10^{20}$ eV $\nu$’s
- regolith attenu. len. $\sim 20$ m
- $\sim 123$ hours livetime
- $[V\Delta\Omega]_{\text{eff}} \sim 600$ km$^3$-sr
- datataking complete

A more detailed view of GLUE
(since common to most radio detection)
FORTE satellite
(Fast On-orbit Recording of Transient Events)

- Main mission: synaptic lightning observation
- Viewed Greenland ice with appropriate trigger (1997-99)
  - 1.9 MILLION km$^3$
  - 38 days $\times$ 6%
- Can self-trigger on transient events 22MHz band in VHF band (from 30 to 300 MHz)
- Event characterization
  - polarization
  - ionospheric group delay and birefringence
  - timing

N. Lehtinen et al., PRD 69, 013008 (2004)
Example Forte Event

\[ E_{\nu}^{\text{thresh}} \sim 10^{22} \text{ eV} \]

\([\nu \Delta \Omega] \sim 100,000 \text{ km}^3 \text{ sr}, \text{ but threshold extremely high.}\]
$E_\nu > 10^{17}$ eV

$[V \Delta \Omega] \sim 20,000 \text{ km}^3\text{-sr}$

ANITA Schedule

- December: 2003-04  Anita-lite *(completed)*
- Ongoing: payload construction
- June 2005  Test run at Ft. Sumner, NM
- June 2006  Final test at Palestine, TX
- Dec 2006  First flight
- Future seasons: 2 more flights
Anita-LITE

- 18 day flight, Dec. 03 - Jan. 04
- Piggyback on TIGER
- Experience assembling the payload on the ice
- Calibration studies included observation of ground pulse and Sun
- Analysis of Anita-lite data
  - Backgrounds
  - Timing resolution
  - Angular resolution
Anita Lite
Signal and Noise

- Some on-board impulsive noise, will be removed for dedicated ANITA flight
- No evidence for off-payload impulsive noise beyond McMurdo Station horizon
Anita Lite
Resolutions

Ground-to-payload pulse at ~250km from Williams’ Field

375 MHz “tone burst”

- Anita goal 300ps per antenna
- Anita-lite already 120 psec

Anita resolution on RF direction

\[ \delta \theta \sim 0.5^\circ \]

\[ \delta \phi \sim 2^\circ \]
**SALSA:**  
A possible salt detector

- ~25km$^3$ in upper 3km of dome (75 km$^3$ water-equiv.)
  - >2× denser than ice
  - easier to deploy than S.Pole
- Many competing effects make it not obvious which frequency is optimal:
  - attenuation, antenna effective height, Ch. emission formula, Ch. cone width, bandwidth, thermal noise
  - Toy Monte Carlo used to study these events
- As long as attenuation length is smaller than dome, then optimum at longer wavelengths
- Calorimetric; large V,$\Delta \Omega$; Cherenkov polarization usable for tracking
- US likely TX or LA. Dutch investigating sites as well

**diapir action pushes out water**
Salt Dome Detector
Noise and attenuation length measurements

P. Gorham et al., NIMA 490, 476 (2002)

- Attenuation >250m (>500 m w.e.)
  (even at 750 MHz)
- No evidence of birefringence or scattering
- RF environment protected by overburden. Noise level consistent with 300K.

- Estimated events/year
  - $100 \, R_X \implies 50/yr$ above $10^{17}$ eV from AGN
  - $1000 \, R_X \implies 50/yr$ above $10^{17}$ eV from GZK or 5-10 GRB
Another Good Idea from Askaryan (II):
Acoustic Detection
(1957)

- Verified in beamtests at Brookhaven (J. Learned)
SAUND
(Study of Acoustic Underwater Neutrino Detection)

- 7 Hydrophones, subset U.S. Navy array (AUTEC)
- Detection 7kHz to 50 kHz
- Noise floor $\nu^{-1.7}$, sets threshold $\sim 10^{23}$ eV
- Physics run 195 days

J. Vandenbrouke et al., astro-ph/0406105
SAUND Calibration

~\(10^{21}\) eV!

- Attenuation length >500-1000m
SAUND
Neutrino Search

- $E_\nu \sim 10^{22}$ eV
- $[V \Delta \Omega] \sim 100$ km$^3$-sr
- Not enough…
  
  but salt domes may prove $10 \times$ more signal and much less background
Other Acoustic Efforts  
(Acoustic workshop Sept '03)

- SADCO: Black Sea Oil Platforms and Kamchatka
- Hockley/Oakwood Domes. (Measurements begun)
- Europe
  - Mediterranean: Nemo, Antares
  - European Salt domes
  - Rona UK
- PZT sensors on Amanda under study

Summary slides at
Developing Ideas

• Drone flights over deepest Antarctic Ice
  - use the best ice: 4km deep
  - closer ➔ lower threshold
  - instrument can be maintained

• Europa orbiter

Stay Tuned…
An attempt at “model-independent differential” limits:

CURRENT RESULTS

- Best limits to date above $\sim 10^{15}$ eV are mostly due to radio techniques.
Why doesn’t everyone like “model-independent differential” limits?

- Limits can be lowered by just changing the bin size
- Standard “green’s fcn” technique can have significant under or over coverage at 90% C.L.
  - Flat aperture and $E^{-3}$ spectrum violates these limits by factor of two.
  - But in all practical cases so far these have had over-coverage (conservative, but under-represents discriminating power.)
Comparison of Detector Discovery Potential: $[\Delta \Omega \times \Delta t_{\text{live}}$]

\[ \nu_e + \nu_\mu + \nu_\tau \quad \text{(Area \* Steradians \* Livetime)}/N_{90} \]

(Some current, others projected)

- These are for 90\%CL detection (i.e., divided by 2.3 if no bckgd)
- Only radio & acoustic limits currently above $10^{16}$ eV
- Will update a little for proceedings

Plots for other flavors etc. at http://www.physics.ucla.edu/~saltzbrg/uhenu.ps
### Comparing using Models

<table>
<thead>
<tr>
<th>Telescope</th>
<th>Duration</th>
<th>$N_{\text{events}}$</th>
<th>Top. Def.</th>
<th>GZK</th>
<th>GRB/AGN</th>
</tr>
</thead>
<tbody>
<tr>
<td>Anita</td>
<td>45 live days</td>
<td>(PS)</td>
<td></td>
<td>4.8</td>
<td>18</td>
</tr>
<tr>
<td>Amanda B10</td>
<td>130 live days</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Auger</td>
<td>3 live years</td>
<td>0.7</td>
<td>1.0</td>
<td>3.0</td>
<td>1.1</td>
</tr>
<tr>
<td>EAS-TOP</td>
<td>326 live days</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Euso</td>
<td>2.7 live years</td>
<td>18</td>
<td>0.9</td>
<td>3.6</td>
<td>1.9</td>
</tr>
<tr>
<td>Glue</td>
<td>80 hours</td>
<td>0.11</td>
<td>-</td>
<td>0.011</td>
<td>-</td>
</tr>
<tr>
<td>Ice Cube</td>
<td>3 live years</td>
<td>1.1</td>
<td>0.5</td>
<td>1.3</td>
<td>0.020</td>
</tr>
<tr>
<td>Macro</td>
<td>5.8 live years</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.020</td>
</tr>
<tr>
<td>Rice</td>
<td>2.5 live years</td>
<td>2.7</td>
<td>0.7</td>
<td>2.3</td>
<td>0.97</td>
</tr>
<tr>
<td>Salsa-1000</td>
<td>2 live years</td>
<td>34</td>
<td></td>
<td></td>
<td>38</td>
</tr>
</tbody>
</table>

*Will update a little for proceedings*
Proposal for how ν telescopes should report sensitivity

- “Model Independent” limits have pitfalls.

- We should report
  - $N_{\text{events}}$ various models
  - Report $[A \Delta \Omega]$ or for each neutrino flavor
    - state which cross section calculation is being used.
    - includes interaction probability
    - also includes upstream shielding
  - variations with $\pm 20\%$ on $\nu$ cross section
    - result may go up or down depending on experiment

- Give background prediction vs. energy threshold
• Conclusion-I (for a particle physicist):
  Æ UHE ν may provide a unique high-energy lab
    - Probe total cross section & new physics at highest Ecm
    - May detect super-heavy decaying particles as source of UHE ν and CRC

• Conclusion-II (for an astronomer):
Backup Slides
Z-bursts?

If local enhancement of local CNB:

$$\sqrt{2m_{\nu}^{\text{CNB}} E_{\nu}^{\text{UHECR}}} = M_Z \sim 10^{11} \text{ eV}$$

if $m_{\nu}^{\text{CNB}} \sim 0.05 - 0.5 \text{ eV}$

$\Rightarrow E_{\nu} \sim 10^{22-23} \text{ eV}$

$\Rightarrow$ Would be a minimum flux of $10^{23} \text{ eV}$ neutrinos