Radio Detection of Ultra-high Energy Cosmic Rays & Neutrinos

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(Ultra-) High Energy Astrophysics of Cosmic rays & Neutrinos

- 40 years of $10^{18-20}$ eV cosmic ray measurements:
  - Extragalactic, but do we see the GZK absorption edge?
  - $p\gamma$ interactions at $E \approx 1$ GeV c.o.m.
    - ==> well known physics!
    - But a Lorentz factor of $\sim 10^{11}$...

- Neutrinos at $10^{17-19}$ eV guaranteed by GZK process--if we are not in a special part of the universe (standard model)
Role of neutrinos in AGN
black hole studies & UHECR

- “Standard model” AGN: black-hole accretion-disk accelerator
- Black holes--QSO engines, accelerate everything in high-density environment
- Neutrinos unattenuated from anywhere: both BH event horizon & GZK propagation process

\[ \begin{align*}
\text{p, n, e, } \gamma, \nu \\
\gamma \gamma &\rightarrow \text{e} + \text{e}^- \\
\text{n} &\rightarrow \text{e} + \nu \\
\text{p} \gamma &\rightarrow \pi^+ \pi^0 \nu \gamma \\
\end{align*} \]
Neutrinos are all we have at >PeV energies

- Astronomy as we know it ends at ~100 TeV
- Photons absorbed by pair production on IR & μ wave background; particles scattered by B-fields or GZK
- But the energetics of the sources clearly extend to ~10^9 TeV or more
- Ergo: we need neutrinos
What do we need for a GZK $\nu$ detector?

- Standard model GZK $\nu$ flux: $<1$ per km$^2$ per day over $2\pi$ steradian
  - Interaction probability per km of water: $\sim0.2\%$

  $\Rightarrow$ 1 cubic km detector: $\sim0.5$ event per year in its fiducial volume

**we need a teraton (1000 km$^3$) target!**

- How do we scale up from current water Cherenkov detectors?

- **Answer:** *Askaryan process: coherent radio* Cherenkov emission
  - EM cascades produce a charge asymmetry, thus a radio pulse
  - Process is coherent $\Rightarrow$ Quadratic rise of power with cascade energy
  - Neutrinos can shower in radio-transparent media: air, ice, rock salt, etc.

  $\Rightarrow$ RF economy of scale very competitive for giant detectors
Showers in solid media

Simulation: in rock salt, 0.2-1GHz, 1EeV cascade

- Ice: $n = 1.78$,
  \[ \cos^{-1}(1/n) = 53^\circ \]
- Halite (rock salt): $n=2.45$,
  \[ \cos^{-1}(1/n) = 66^\circ \]
- RF Cherenkov cone: propagates through solid, refracts at interfaces

![Diagram of neutrino cascade](image-url)
Askaryan Confirmation: SLAC T444 (2000)

- Use 3.6 tons of silica sand, brem photons to avoid any charge entering target
  ==> no transition radiation
- Monitor all backgrounds carefully
  - but signals were much stronger!

From Saltzberg, Gorham, Walz et al  PRL 2001

P. Gorham, SLAC 2004 Summer school
Shower profile observed by radio (~2GHz)

- Measured pulse field strengths follow shower profile very closely
- Charge excess also closely correlated to shower profile (EGS simulation)
- Polarization completely consistent with Cherenkov—can track particle source
Cherenkov polarization tracking

- Radio Cherenkov: polarization measurements are straightforward

- Two antennas at different parts of cone:
  - Will measure different projected plane of E, S
  - Intersection of these planes defines shower track

Cherenkov radiation predictions:
- 100% linearly polarized
- Plane of polarization aligned with plane containing Poynting vector S and particle/cascade velocity U
SLAC T460: Askaryan radiation polarization tracking

SLAC T460, Gorham et al. 2003

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Askaryan process: where does it win?

Huge dynamic range, linearity

SNR dominant at \( E > 10 \text{ PeV} \)

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RICE effective volume

\[ V_{\text{eff}} \Omega \sim 6 \text{ km}^3 \text{ sr} \ @ \ E_\nu \sim 1-2 \text{ EeV} \]

- Large >EeV effective volume based on ice transparency
- \( L_{\text{atten}} \sim 1\text{ km} \) at 300 MHz
- Systematics of \( \sim 4-5\text{ km} \) horizontal propagation still need study

\begin{align*}
\log (E_{\text{shower, PeV}}) & \sim 0.2 \ E_\nu \\
\log |V_{\text{eff}}| & (\text{km}^3) \\
\end{align*}

RICE fiducial V \sim 100m radius

\sim 1\text{ km} \hspace{1cm} \sim 8-10\text{ km}
FORTE: A space-based EHE neutrino & cosmic ray detector?

Fast On-orbit Recording of Transient Events

• Pegasus launch in mid-1997, 800km orbit
  - Testbed for nuclear verification sensing
  - US DOE funded, LANL/Sandia ops
  - Scientific program in lightning & related atmospheric discharges

• 30-300 MHz (VHF) frequency range
  - ~3M impulsive triggers recorded to date

• FORTE can trigger on radio emission from giant air showers at E~100 EeV
  - Preliminary estimates: could be ~50 $10^{20}$ eV cosmic ray events in sample
  - Distinct from lightning, could be recognized as isolated events in clear weather regions far from urban noise
  - Analysis (JPL, LANL) planned this year
Shower Radio Detection by FORTE

- Simulations indicate that FORTE could be highly sensitive to post-GZK spectrum
- Sensitivity limited by \(~10\%\) livetime, RF interference, & uncertainty in radio emission process

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FORTE: Lightning events

- Satellite can trigger on impulsive events even when strong VHF carrier signals are present

- Plots show Frequency spectrum vs time—curvature on impulses due to ionosphere
  - Aids in geolocation—unique B signature for each satellite position
FORTE: Search for neutrino candidate events from Greenland ice sheet

- 3.8 days total livetime

- Threshold high:
  - $\sim 10^{22.5}$ eV

- 2 candidates survive out of $\sim 2500$ initial events
  - Require high polarization, non-lightning, geolocation

- N. Lehtinen, in prep. for PRD 2003
Goldstone Lunar Ultra-high energy neutrino Experiment (GLUE)-- A ZeV example…

- Use NASA Deep Space Network antennas to search for Askaryan pulses from neutrinos interacting in lunar regolith

- Use coincidence to beat RF interference

- Askaryan suggested the moon; I. Zheleznykh (‘88) showed we don’t have to go there with antennas

- Hankins & Ekers tried with Parkes in 1996
GLUE details

- Effective target volume: Antenna beam (~0.3 deg) times ~10 m moon surface layer
  ==> ~100,000 cubic km!!

- RF pulse spectrum & shape

- Regolith is transparent in L and S band (10-26 cm)

- Dual antenna use eliminates terrestrial RFI
Lunar Regolith Interactions & RF Cherenkov radiation

- At ~100 EeV energy, neutrino interaction length in lunar material is ~60km
- $R_{\text{moon}} \sim 1740$ km, so most detectable interactions are grazing rays, but detection not limited to just limb
- 120 hours of livetime to date in 3 years (competes with spacecraft telecom)
Salt domes: found throughout the world

- Qeshm Island, Hormuz strait, Iran, 7km diameter
- Isacksen salt dome, Elf Ringnes Island, Canada, 8 by 5km

- 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 km³ water equivalent in top ~3km

Halite (rock salt)
- $L_\alpha(<1\text{GHz}) > 500 \text{ m w.e.}$
- Depth to >10 km
- Diameter: 3-8 km
- $V_{\text{eff}} \sim 100-200 \text{ km³ w.e.}$
- No known background
- >2π steradians possible
2001 Hockley salt dome rock salt tests

- 150, 300, 750MHz all 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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Salt dome demographics:

- Several hundred known—some are good source of oil
- Typical ~3-5 km diameters, 5-15 km deep
- ~200 km³ water equiv. in top 3-5 km for many domes
ANITA Mission Design

- ANITA depends uniquely on Antarctica
- Balloon altitude nearly optimal
- Ice thickness avg = 1500m under typical LDB track
Mission & Flight Payload Design

- Quad-ridged horn antennas provide superb impulse response & bandwidth
- Interferometry/beam gradiometry from multiple overlapped antenna measurements
ANITA concept & basis

Ice RF clarity: 
\[ \sim 1\text{km}(!){\text{atten. length}} \]

Effective “telescope” aperture \((\text{km}^3\text{ sr})\):
- \[ \sim 250 @ 10^{18} \text{ eV} \]
- \[ \sim 10^4 @ 10^{19} \text{ eV} \]

(compare to \[ \sim 1\text{km}^3 \text{ at lower E} \])

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ANITA-lite EMI balloon survey

NASA provided a piggyback mission of opportunity for ANITA on the ‘03-’04 Trans-Iron Galactic Element Recorder (TIGER) flight…

- ANITA-lite flew ANITA prototypes & OTS hardware
  - 2 dual polarization prototype ANITA antennas
  - 4 channels total at 2 GHz sampling, 1 GHz bandwidth

- Measured ambient RF interference & thermal noise
- 18 days flight time, 130K events recorded
- External drive recovered w/ 80% of data
  - 20% still in cold storage, awaiting instrument recovery
- Results look excellent so far…
TIGER/ANITA-lite launch preparation
TIGER ANITA-lite launch
ANITA-lite impulse analysis

- Dominated by payload local noise
- Circularly polarized impulses (TDRSS relay turn-on?) are closest to true impulses (but not)
- Glitches from balloon support package (charge controller MOSFETS)
- Injected 3 and 5 sigma signals (overlain on actual thermal noise) used to test algorithm efficiency
- Accidental rate: 3-fold, 5 sigma:
  - < 1 per week
Impulse analysis (cont.)

- Impulse cuts:
  - Power at trigger/power in tail > 1.6
  - Risetime of highest V peak < 3ns
  - Cross correlation with known impulse response improves SNR
  - Power in tail / power in pre-trigger noise < 2

<table>
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<th>Total: 97163 events</th>
<th>Ch1</th>
<th>Ch2</th>
<th>Ch4</th>
<th>Ch1+ch2</th>
<th>Ch2+ch4</th>
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BKG rejection: 100%

SIG efficiency: ~70%
Antarctic Black Hole factory?

- Suppose that photons are confined to 4-space, D=4
- But gravity propagates in n extra dimensions of size L
- For r>>L, \( F_{\text{grav}} \sim r^{-2} \), but r<<L, \( F_{\text{grav}} \sim r^{-(2+n)} \)
- Now: particle collisions can make a black hole (BH) if \( E_{\text{cm}} > m_{\text{strong}} \)
- For D=4+n, \( m_{\text{strong}} \sim \text{TeV} \) is possible!
- For GZK neutrinos on protons
  - \( E_{\text{cm}} \sim 100 \text{ TeV} \)
  - \( \Rightarrow \) GZK neutrinos can make BH with up to 2 order of mag higher cross section than standard model neutrinos
  - Will immediately decay & shower
- Anita-lite may constrain highest predictions!
ANITA/ANITA-lite sensitivity (preliminary)

- Approximately 18 days of data, net 40% livetime \(\rightarrow\) 1 week
- Simulation threshold \(\sim\) 5 sigma per channel
- No candidates survive impulse cuts
- \(\sim\)65% of 5 sigma injected signals survive
- If signal were at GLUE/RICE limits, ANITA-lite sees \(\sim\)10-20 events
  - Highest TD model probably excluded
- RICE limits for 3500 hours livetime
- GLUE limits \(\sim\)120 hours livetime
- FORTE (N Lehtinen, UH) limits on \(\sim\)3 days of satellite observations of Greenland ice sheet

- **ANITA sensitivity:**
  - \(\nu_\mu\) & \(\nu_e\) included, full-mixing parameterized
  - 1.5-2.5 orders of magnitude gain
Summary

Radio detection: The most cost-effective way to do PeV ($10^{15}$ eV) to ZeV ($10^{21}$ eV) astronomy

UHE neutrino models already constrained by existing detectors

ANITA-lite 2003: most sensitive EeV to date!?

ANITA 2006: the GZK BH factory?!