Radio Cherenkov searches for cosmogenic ultra-high energy neutrinos, & ANITA results

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Ultra-high Energy Cosmic rays require Neutrinos

Neither origin nor acceleration mechanism known for cosmic rays above $10^{19}$ eV, after 40 years!

A paradox:
- No nearby sources observed
  - Auger: yes!?, HiRes: No!
- Distant sources excluded due to collisions with microwave bkg

Neutrinos at $10^{17-19}$ eV required* by standard-model physics
- Lack of neutrinos:
  - UHECRs all heavy nuclei?
  - "Just so" source spectra?
  - Lorentz invariance wrong?!?
  - New physics?

* Berezinsky & Zatsepin 1970, many others since
UHECR and the “GZK horizon”

- UHECR provide local source information, current epoch
  - Universal UHECR Accelerators likely to evolve in many ways: strength, metallicity, number density, ...
- BZ neutrino spectra are direct from sources at all epochs
At energies above $10^{14-15}$ eV:

- Universe becomes opaque to photons beyond few tens of kpc
- CR protons, nuclei are galactic up to $\sim 10^{18}$ eV, suffer GZK cutoff above that
- Neutrinos unabsorbed at all energies
- Sources exist to at least $3\times10^{20}$ eV

• Conclusion: UHE neutrinos are the only viable messenger beyond the local universe
Why go after *cosmogenic* UHE neutrinos?

- Trace particle UHECR hyper-accelerators to very early epochs
  - Even at $z \approx 10$ or more, GZK neutrino energies peak at 10-100 PeV
  - they all point back directly to the UHECR sources

- Their flux is constrained by UHECR sources, once determined
  - Can become a quasi-isotropic "test beam" of UHE neutrinos
  - $\sim 100$-$1000$ TeV center-of-momentum-frame energies on nucleons

- Flavor Oscillations! (who ordered that?)
  - A new kind of messenger, unlike photons—surprises await
  - Flavor ratios encode source information, even new physics

- **Proper detector scale:** 1 km$^3$? No, try $\sim 1000$ km$^3$

- **Cannot easily scale up optical IceCube**

- $\rightarrow$ scalable new detection method: radio Cherenkov
Askaryan Effect: confirmed in 2001 at SLAC

Coherent radio emission from excess negative charge in an EM shower:
- e- upscattered into shower, e+ annihilated → 20% -ve asymmetry
- “Shower” is actually a thin disk of HE particles
  - A few mm thick and few cm wide in solids
- At radio wavelengths longer than ~10-20 cm:
  - **appears as a single charge of Z~10^8 → Z^2=10^{16} x single e-**
Askaryan effect: experiments

Lunar, with ground-based dishes:

- Parkes 64m dish: Hankins, Ekers, O’Sullivan 1996 (first suggested by Zkeleznyk & Dagkesamanski, Neutrino ‘88 Boston)
- GLUE: Goldstone Lunar Ultra-high energy neutrino expt. 1998-2002, 120 hrs with 70m+34 m radio dishes
- 64m Kalyazin telescope, Russia, 2003-2005
- More to come: Westerbork, EVLA, LOFAR, SKA, and SPACE-BASED?

Ice: Antarctica & Greenland

- Radio Ice Cherenkov Experiment (RICE) (completed 2006)
  - Constrained highest GZK neutrino models
- Fast On-orbit Recording of Transient Events (FORTE) 2004
  - DOE satellite with impulse trigger, 3.8 days obs. Of Greenland, UHE limits >1e21 eV
- Antarctic Impulsive Transient Antenna—ANITA
  - ANITA-lite flew in 2003-2004, 4 channel prototype
  - First Full ANITA flight completed late January 2007
  - ANITA-2 now completed, January 2009
- Future: ARA (eg, super-RICE), EeVA, others...
ANTARCTIC IMPULSIVE TRANSIENT ANTENNA--ANITA

ANITA
Gondola & Payload

Overall height ~8m

NASA start in 2003, 1st launch in ‘06-07, 2nd in ‘08-09; baseline 10 day mission, got 35 + 31 days total

Ultra-broadband antenna array, views 1.5 M km² of ice sheet looking for Askaryan impulses, Δf ~ 0.2-1.2GHz


Ice RF clarity:
1.2 km(!) attenuation
Length @ 300 MHz
ANITA as a neutrino radio telescope

Pulse-phase interferometer (<30-60 ps timing) gives intrinsic resolution of <0.3° elevation by ~1° azimuth for arrival direction of radio pulse

Neutrino direction constrained to ~<2° in elevation by earth absorption, and by ~5-7° in azimuth by observed polarization angle of detected impulse
Pulse phase interferometry

- RF Waveform samplers (G. Varner, UHM)
  - Provide 10 bits, 2.6 Gsamples/sec for 80 channels
- Waveform cross-correlation delay precision determines angular resolution
  - \(~30-40\) ps vertical at SNR\(~5\sigma\)
  - \(~60-80\) ps horizontal (due to DAQ clock alignment errors)

0.2-1.2 GHz bandwidth \(\Rightarrow 1\) ns impulses
June 2006, SLAC T486: “Little Antarctica”

End Station A, SLAC

- SLAC $e^-$ showers with composite energy same as UHE neutrinos
  - $10^{8-9} \times 28$ GeV
  - $=2.8 \times 10^{19}$ eV

- Coherent radio power, consistent with theory

- 1st direct observation of radio Cherenkov cone

Thanks to P. Chen, C. Hast, SLAC

P. Gorham, NDM 2009
Pre-launch rollout

- Launch from ~80m deep Ross ice shelf (floats on Ross sea)
- ~8 miles from McMurdo station
- Affords flat, stable 1-mile diameter launch pad

Photos: J. Kowalski
ANITA-1 flight path

- 35 days, 3.5 orbits, but anomalous Polar Vortex conditions
- Stayed much further “west” than average
- In view of radio noise from stations (S. Pole & MCM) ~50% of time
- But still achieved 18 days of good livetime at ~1.2km average depth of ice
Flight sensitivity snapshot

- ANITA sensitivity floor defined by thermal (kT) noise from ice+sky+rcvr
  - $T_{rcvr} \sim 140K$
  - $T_{ice} \sim 230K$
  - $T_{sky} \sim 20-80K$
- Thermal noise floor seen intermittently throughout of flight—but punctuated by station noise
  - South Pole and McMurdo stations!
- Still a significant fraction (~50-60%) of time with pristine conditions
Solar Sensitivity calibration

ANITA (~3-5m cluster) interferometric images of the radio sun
- Flight averages shown here
- Sun detection required about 200 sec of thermal noise data
- Provides 1st-order absolute calibration of antenna noise, beam response, event timing
- Note also horizon (and its sidelobes) at -6 degrees!

Images from S. Hoover, UCLA
ANITA geo-location of borehole cal events

- Expect ~ $c\Delta\tau/2D$ altitude & azimuth
- $\Delta\tau \sim 40-60$ ps, $D \sim 1$ m (horizontal) to 3 m (vertical)
- Altitude: 0.21° observed, 0.3° expected
- Azimuth: 0.8° observed, 1.7° expected
- Multiple baselines improve constraints
- Pulse-phase interferometry works well!

Thanks to JiWoo Nam, NTU
Event reconstruction & analysis

- Raw data: RF plane-wave lights up one side of payload
- Waveform correlator (offline) gives 30-60ps timing
- Reconstruct ground position & error ellipse
- If $<3\sigma$ from camp or any other event, reject
- South pole EMI, calibrated borehole pulser at MCM used to calibrate timing & statistical behavior
Initial unblinded higher-threshold event set

~19K events (9.6K Vpol & 10K Hpol) are impulsive & reconstruct to Antarctic ice locations

- Exclude all repeating locations (H,V,H+V)
- Exclude single events within ~50km from known sites
- After cluster+camp rejection:
  - 0 V-polarized (no askaryan-like signals ➔ no neutrinos)
  - 6 H-polarized events left

“camp” = any man-made installation, active or not
  - most are inactive, many may be gone in fact
  - but exposed metals could discharge

Jiwoo Nam, NTU
ANITA-1 lower threshold analysis

Independent deeper analysis done at UCLA

Detected: **no neutrino candidates**, all of original 6 Hpol events, **+8 more**

Hpol events: good coherence, not like any anthropogenic signals, low-frequency-dominated
Horizontal Polarization??

- Askaryan (e.g., neutrino) signals strongly favor vertical polarization
  - Only top quadrant of Cherenkov “clock-face” escapes TIR at surface
  - Fresnel coefficient transmits more Vpol (TM) than Hpol (TE)

- Reflections from above-the-horizon sources tend to strongly favor horizontal polarization
  - $R_{TE}/R_{TM} > 3:1$ over most of ANITA acceptance
  - $\Rightarrow$ Hpol events cannot be neutrino candidates but could be
    - Air shower radio (geo-synchrotron)
    - Solid-state relays on satellites
ANITA as a UHECR telescope?

- Toy Monte Carlo: if EAS radio emission has a partially coherent tail $\rightarrow$ 1 GHz (e.g. Data from 1960’s), ANITA would see it.
- Acceptance is comparable to Auger: $\sim$10-15K km$^2$ sr at 10$^{20}$ eV
- But time exposure far less than Auger, & no good energy cal
- Virtue: it proves ANITA was sensitive to UHE neutrinos as well!
Where we are after the ANITA-1 flight...

- ANITA-1 has begun to constrain highest, less likely models.

- ANITA-2 (Flight completed in January 2009) will begin to probe "standard model" range.

- ANITA-2 Unblinding expected within a month.

- GZK neutrino “envelope” contains nearly all cosmogenic neutrino models proposed to date (from Berezinsky’s mirror matter at high end, to pure iron UHECR at low end).
ANITA 2 (2008-2009) improvements

- **Improve system temperature by 40K (new front end)**
- Improve efficiency ~20%
  - active direction mask for trigger to blank out direction of camps & stations
- Improve trigger sensitivity by ~30% (Vpol-based trigger)
- Drop-down antenna ring: ~30% sensitivity increase

⇒ Net improvement:
  - Factor of ~1.7 in energy threshold (Tsys+trigger+drop-down)
  - ANITA gains as $\sim E_{\text{thr}}^{-2} \Rightarrow 1.7^2 = \text{factor of 3 in event rate increase}$
  - 30% in exposure for better flight trajectory & direction mask
  - 40% improvement in livetime possible
  - $3 \times 1.3 \times 1.4 = \text{factor of } >5 \text{ in neutrino event rate}$
ANITA-2 launch Dec. 2008
ANITA-II

- ANITA-II: 31 days at float, >70% in radio-quiet conditions
- Collected 3x as much data as ANITA-1
- Angular resolution ~50% better
  - Less ice “lost” to camp peripheries

Expect to realize most or all of predicted sensitivity increase
Askaryan Radio Array (ARA)

- NSF MRI proposal Aug. 09
- US: Wisconsin, Maryland, Hawaii, Kansas, Delaware & others
- UK, German, Belgian, Dutch, & Taiwan support as well
- Low Cost ~80 km² radio Cherenkov array at SP
- Goal: establish the cosmogenic neutrino flux
Drill Table

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<th>Total Stations</th>
<th>Total Holes (with plunger)</th>
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Cable Note: 17.5 km of Surface Cables From ICL to 7 Stations

(3) 200m Deep 4" diameter Holes

Super Cluster Detail
EeVA: ExaVolt Antenna, a NASA ULDB Mission
A toroidal balloon-surface reflector as a neutrino telescope

- Toroidal ~10 m high reflective band
- Inner balloon or membrane supports feed array
- Effective collecting area for any direction >100 m², but aberrations reduce gain
- **ULDB necessary** for stable shape
- Antenna modeling gives ~27 dBi net gain—achieves goal

EeVA improves a factor of ~100 on existing ANITA-1 BZ neutrino limits

Numerical Electromagnetics NEC2 model (includes ULDB shape and surface)

Polar plot of elevation response pattern
Compiled limits & future sensitivity

- Highest BZ models now excluded, RICE + ANITA-1
- Near term: ANITA-2,3 should probe “standard model” range
- Future: Exavolt Antenna will continue NASA’s sole neutrino astronomy initiative
- Askaryan Radio Array: will engender a new phase of precision measurements

EeVA, 60 days exposure
Summary

- Askaryan’s hypothesis about coherent radio Cherenkov from UHE showers is now proven solid.
- Cosmogenic neutrino flux (the ‘guaranteed’ neutrinos) within reach.
- ANITA-1 has come close to detection, source evolution constraints forthcoming.
- ANITA-2 will soon begin to dig deeper into GZK model space.
- Future initiatives abound: we are going to see these neutrinos soon!
Moon vs. Antarctica…

- Area of Antarctica ~ visible area of Moon

- Antarctic ice:
  - Latten ~ >1200 m at 400 MHz
  - Depth ~ 3 km

- Lunar Regolith:
  - Latten ~ 20-30 m at 400 MHz
  - Depth ~ few tens of m to bedrock

- Conclusion: at GZK neutrino energies, Antarctica wins!
ANITA-1 Launch: December 15, 2006

ANITA at float (123Kft)
- See through amateur telescope from the South Pole
- Size of the Rose Bowl (really!)
  (thanks to James Roth)

Photos: J. Kowalski
K. Palladino & D. Saltzberg
Landing...~360 miles from South Pole

Ouch! Chute did not release after landing, payload dragged ~1 mile
BUT: DAQ & data OK → success

Photos: D. Braun