Radio Detection of UHE Neutrinos and Cosmic Rays of Taiwan
ANITA, ARA, T-510, SFLASH & TAROGE

T.C. Liu
LeCosPA,
National Taiwan University

TKU Seminar, Spring 2018
Outline

1. Introduction of Cosmic Rays and Neutrinos
   - What??
   - Why??
   - How???

2. Experiments
   - ANITA (The ANtarctic Impulsive Transient Antenna) at 32km
   - ARA at -200m
   - T-510 Radio Emission from Particle Cascades in the Presence of a Magnetic Field
   - Fluorescence in Air from Showers (sFLASH)
   - Taiwan Astroparticle Radio wave Observatory for Geo-synchrotron Emission(TAROGE)

3. Summary & Future Plans
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3. Summary & Future Plans

T.C. Liu  UHE Neutrinos Experiment
Cosmic Rays

**Definition** Cosmic rays are high-energy radiation, mainly originating outside the Solar System.

**Source** Crab Nebula, supernovae, active galactic nuclei, quasars, gamma-ray bursts...
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**Composition** 90% are protons, 9% are alpha particles, 1% are the nuclei of heavier elements.
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Figure: Pauli hypothesized an undetected particle that he called a "neutron" in keeping with convention.
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Figure: When the third type of lepton, the tau, was discovered in 1975 at the SLAC, it was expected to have an associated neutrino (the tau neutrino).
How Many Generations?

Figure: When the third type of lepton, the tau, was discovered in 1975 at the SLAC, it was expected to have an associated neutrino (the tau neutrino).
Neutrino Flux is not Conserved ?!

**Figure:** Measurements of solar neutrino types were not consistent with models of the Sun’s interior
Super nova neutrino

**Figure:** Super-Kamiokande observed super nova neutrino.
Super nova neutrino

2002 Nobel Prize

Figure: Super-Kamiokande observed super nova neutrino and confirm the...
Fundamental Forces

**Strong**
- Force which holds nucleus together
- Strength: $1$
- Range (m): $10^{-15}$ (diameter of a medium sized nucleus)
- Particle: gluons, $\pi$(nucleons)

**Electromagnetic**
- Strength: $1/137$
- Range (m): Infinite
- Particle: photon, mass = 0, spin = 1

**Weak**
- Neutrino interaction induces beta decay
- Strength: $10^{-6}$
- Range (m): $10^{-18}$ (0.1% of the diameter of a proton)
- Particle: intermediate vector bosons $W^+, W^-, Z^0$, mass $> 80$ GeV, spin = 1

**Gravity**
- Strength: $6 \times 10^{-39}$
- Range (m): Infinite
- Particle: graviton?, mass = 0, spin = 2

*Figure: Fundamental Forces.*

T.C. Liu
UHE Neutrinos Experiment
Interaction Length of Neutrinos

Figure: The neutrino interaction length (in centimeters water equivalent distance) [Astropart.Phys. 35 (2012) 383-395]

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UHE Neutrinos Experiment
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3 Summary & Future Plans
Why? Cosmic rays

- **Acceleration** How to accelerate the particles?
- **Origin** Where are the particles from?
- **Stellar Magnetic fields** By studying the path of cosmic rays.
- **Relation with dark matter** Galactic nuclei are capable of converting dark matter into high energy protons.
- **Testing Hadronic Interactions** PAO has detected more muons from cosmic-ray showers than predicted by the most up-to-date particle-physics models.
Figure: Cosmic rays ionize the nitrogen and oxygen molecules in the atmosphere, Ex: $^{14}\text{C}$
Figure: Cosmic ray muons have been used for decades to radiograph objects such as pyramids.
Muon Tomography

Figure: view of the Showa-Shinzan lava dome
Cosmic Rays & Climate

Figure: The correlation between cosmic ray flux and the low altitude cloud cover using ISCCP satellite data set.
Cosmic Rays & Lightning?

*Figure:* Cosmic rays have been implicated in the triggering of electrical
**Why?? Neutrinos**

- GZK cut-off & Missing Spectrum
- Neutrino Mass
- Neutrino Hierarchy
- Mixing Angles
- Neutrino Decay
- Neutrino Oscillation
- Neutrino Interaction Model
What I want? The Ideal UHE Messenger

- Photons lost above 100 TeV (pair production on CMB & IR)
- Protons and Nuclei suffer curvature induced by B fields
- But: we know there are sources up to $10^{20}$ eV!!

**UHE Neutrino Detectors Study:**
- Highest energy observation of extragalactic sources
- Very distant sources
- Deep into opaque sources

From A. G. Vieregg
UHE Neutrino & GZK Effect

At energies above $\sim 10^{19.5}$ eV cosmic rays will interact with CMB photons producing neutrinos.

Process is known as the GZK effect.

Auger and HiRes measurements of UHE cosmic rays consistent with GZK cut-off.

**Guaranteed GZK neutrino flux, but how large?**

*copy from Jonathan's slides*
**GZK Radius**

**Figure:** The UHE neutrinos can point back to the original UHE source without bending of B field.
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3. Summary & Future Plans
Shower Components

- Secondary cosmic rays
- Nuclear interaction with air molecule
- Hadronic cascade
- Muonic component
- Neutrinos
- Hadronic component
- Electromagnetic component
Shower Simulation

Take a short break, Let’s us watch a video of shower develop.

- 400 GeV shower (\(\Upsilon\), p, and \(C_{13}\))
- 400 GeV \(\Upsilon\) shower
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3. Summary & Future Plans
UHE Neutrino Interact with Earth

Figure: The interaction length of neutrino with $5 \times 10^{13}$ eV is close to diameter of Earth. The interaction length for $10^{19}$ eV neutrino is $6 \times 10^7 \text{ g/cm}^2$. 

From Google Earth

~$10^{19}$ eV neutrino

~$5 \times 10^{13}$ eV

T.C. Liu UHE Neutrinos Experiment
ANITA Collaborations

Figure: University of Hawaii at Manoa, University of California, Los Angeles, The Ohio State University, The University of Delaware, The University of Kansas, Washington University, the NASA Jet Propulsion Laboratory, University College London, University of Chicago, National Taiwan University and the California Polytechnic State University.
McMurdo Stations.
Introduction of Cosmic Rays and Neutrinos Experiments

Summary & Future Plans

The ANtarctic Impulsive Transient Antenna

GPS Antenna

solar panels

ANITA-III box
computer, signal processing

Horn Antennas for Detecting Signal

NASA science instrument package

Figure: ANITA instrument

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UHE Neutrinos Experiment
The ANITA’s Concept

**Figure:** Cherenkov radiation is electromagnetic radiation emitted when a charged particle passes through a dielectric medium at a speed greater than the velocity of light in that medium.
Coherent Radio Emission (Askaryan Radiation)

Figure: Detect radio emission from neutrino induced particle cascades in ice
Askaryan Radiation Experiment in SLAC

PRL 99, 171101 (2007)
see also:
PRE 62, 8590 (2000),
PRL 86, 2802 (2001),
PRD 72, 023002 (2005)
PRD 74, 043002 (2006)

*copy from Ryan's slides*
Signal Type (Neutrino VS. EAS)

**EAS Detection**
- H-pol predominate RF signal by geosynchrotron emission
- V-pol component is further suppressed in the reflection
  - Predominately H-pol

**Neutrino Detection**
- RF Cherenkov by Askaryan Effect
- Low Fresnel coeff. for transverse electric waves at the air-ice boundary.
  - H-pol signal suppressed
  - Predominately V-pol
The ANITAs

**ANITA-I (2006-2007)**

**ANITA-II (2008-2009)**

**ANITA-III (2014-2015)**

- 35 days
- 30 days
- 22 days
Introduction of Cosmic Rays and Neutrinos

Experiments

Summary & Future Plans

Trajectory of ANITAs

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UHE Neutrinos Experiment
FoV of ANITA

- ANITA (The ANtarctic Impulsive Transient Antenna) at 32km
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Figure: The radius of FoV is about 500km.
Man-Made EVENTS of ANITA

- 300k events pass thermal cuts
- Cluster with:
  - Other events
  - Known bases of activity
  - “Hot-Spots”
- Neutrinos are single, isolated events!
Angular reconstruction is a crucial part in the ANITA data analysis.

- Powerful background rejection
  - Incoherent thermal events (99% of data set)
  - Anthropogenic RF events from existing bases
  - Air shower RF events.

- Neutrino reconstruction
  - Neutrino direction information
  - Provides R and refraction angle for energy measurement.

- Angular reconstruction using timing.
  - Time resolution: 40-60 ps
    (time difference between channels)

- Achieved angular resolution;
  - 0.2° (zenith) and 0.8° (azimuth.)

From Jiwoo Nam
Ground Pluser System

- Two Ground Pulser Systems @Williams Field and Taylor Dome
- System Verification
- Trigger Test
- Propagation and Surface
- Timing / Angular Resolution
Angular Resolution

Payload position During this segment

Reconstructed RF source positions

ANITA (The ANtarctic Impulsive Transient Antenna) at 32km
ARA at -200m
T-510 Radio Emission from Particle Cascades in the Presence of a Magnetic Field
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Angular Resolution

<table>
<thead>
<tr>
<th>Constant</th>
<th>Mean</th>
<th>Sigma</th>
</tr>
</thead>
<tbody>
<tr>
<td>187.161</td>
<td>-0.029</td>
<td>0.199</td>
</tr>
</tbody>
</table>

\[ \sigma = 0.2^\circ \]

\[ \sigma = 0.8^\circ \]
Results of ANITA I & II (cosmic rays)

- A combination of $\mathbf{v x B}$ and Fresnel coefficients result in air shower emission being horizontally polarised at the payload
- ANITA-I detected 16 isolated H-pol candidate UHECR events
- ANITA-II did not trigger on the H-pol channels — Doh!!
- Still detected 5 UHECR candidate events
Results of ANITA I & II (Neutrino)

- **ANITA-II Results**
  
  | Isolated v-pol events | 1 |
  | Expected background events | 0.97 ± 0.42 |

- Combine with efficiency to extract world’s best limit on UHE neutrino flux above $10^{19}$ eV
Some Photos of ANITA Project
Introduction of Cosmic Rays and Neutrinos Experiments
Summary & Future Plans

Some Photos of ANITA: Starting Point
Some Photos of ANITA: Payload House
Some Photos of ANITA: Payload House
Some Photos of ANITA-IV
Some Photos of ANITA
Introduction of Cosmic Rays and Neutrinos Experiments

Summary & Future Plans

Some Photos of ANITA-IV
Introduction of Cosmic Rays and Neutrinos

Experiments

Summary & Future Plans

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Some Photos of ANITA-IV

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ARA at -200m

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ARA at -200m, Neutrino
TAROGE ~1km, Cosmic Rays

ANITA ~40km Cosmic Rays, Neutrino

UFFO ~550km, Gamma Ray Burst
Introduction of Cosmic Rays and Neutrinos Experiments

Summary & Future Plans

ARA at -200m

The Askaryan Radio Array (ARA)
Detecting Neutrinos in Antarctica
The ARA Collaboration

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The ARA Collaboration

- T.C. Liu
- UHE Neutrinos Experiment
The Askaryan Radio Array (ARA) is an Ultra High Energy (UHE) Neutrino Detector at the South Pole

Auger and HiRes measurements of UHE cosmic rays consistent with GZK cut-off

Guaranteed GZK neutrino flux, but how large?

At energies above $\sim 10^{19.5}\text{eV}$ cosmic rays will interact with CMB photons producing neutrinos

Process is known as the GZK effect


copy from Jonathan's slides

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UHE Neutrinos Experiment
ARA-37

Figure: ARA 37 Layout, 37 Stations 200m below the surface ~200km^2
ARA Sub-Station – DAQ

- 150-850 MHz bandwidth
- 3.2 GSa/s sampling (4x Nyquist)
- Low power consumption
- Autonomous data taking
Introduction of Cosmic Rays and Neutrinos Experiments

Summary & Future Plans

DAQ System and Antenna Cluster

Figure: Each station has 4 string with 16 channels
Build & Test in Taiwan

Figure: Building ARA2 & ARA3 last year
Introduction of Cosmic Rays and Neutrinos Experiments
Summary & Future Plans

Delivery

Figure: delivery for 2 stations
Drilling and Deployment

- Hot water drill creates 6” wide holes
- Holes are pumped dry
- Approaching ~ 8 hr × ~ 1 drill crew per 200 m hole
- Instrumentation deployed from greenhouse sled
Simulation & Expected Sensitivity

- In-house tool called AraSim
- Simulates
  - neutrino interaction
  - radio emission
  - radio propagation
  - instrument response
  - thermal, instrument noise
  - hardware trigger
  - digitized waveforms
- Has been used to calculate trigger-level neutrino sensitivity
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3 Summary & Future Plans
T-510

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Radio Detection of T-510 (Geo-Synchrotron Radiation)

**Askaryan Radiation**
- Positron annihilation & Compton Scattering leads to 20% charge excess, emits coherently in radio regime

**Geomagnetic Radiation**
- Lorentz Force $\mathbf{v} \times \mathbf{B}$ leads to transverse currents
T-510 Collaborations

- **UCLA**
  - Konstantin Belov (PI)
  - David Saltzberg
  - Stephanie Wissel
  - Joe Lam
  - Kyle Borch
  - Kyle Kuwatani
  - David Urdaneta

- **Washington University in St. Louis**
  - Brian Rauch
  - Bob Binns
  - Martin Israel
  - Viatcheslav Bugaev

- **JPL**
  - Andrew Romero-Wolf
  - Charles Naudet

- **KIT**
  - Tim Huege
  - Anne Zilles

- **UC Berkeley**
  - Carsten Keil
  - Hast Jobe

- **SLAC**
  - Pisin Chen
  - Jiwoo Nam
  - TsungChe Liu

- **W&M**
  - Katharine Mulrey
  - John Clem
  - David Seekel
  - Rachel Hyneman

- **CAL POLY**
  - Stephanie Wissel

- **KU**
  - Dave Besson
  - Mark Stockham
  - Jessica Stockham

- **Taiwan Astroparticle Radio wave Observatory for Geo-synchrotron Emission (TAROGE)**
  - Peter Gorham
  - Harm Schoorlemmer
  - Ben Rotter

- **TAROGE Collaborations**
  - Keith Bechtol
  - Abigail Vieregg

T.C. Liu  UHE Neutrinos Experiment
End Station A (4.55 GeV)

3 km linear accelerator
Setup of T-510

Up to a 970 G vertical “geo” magnetic field created by 15 coils

Beam charge monitors & trigger
4.55 GeV Electron beam

Lead pre shower

X_max

1.4 m to 12.4 m
Magnet of T-510

- Two layers of staggered solenoids to produce uniform magnetic field
- Measured in a 5cm x 5cm grid at beam height
- Primarily vertical to induce radiation in the horizontal direction
Radio Signal of T-510

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UHE Neutrinos Experiment
Radio Signal of T-510

Radio emission from a particle cascade in a dense medium

Observer facing cascade

B=0G

B=1000G

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UHE Neutrinos Experiment
Comparing Data & Simulation

- ZHS and Endpoint formalisms agree to within 3%
- Data peak amplitude exceeds simulation by 35% (commensurate with systematic uncertainty)

Vertically polarized signal on the Cherenkov cone
Introduction of Cosmic Rays and Neutrinos

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Summary & Future Plans
sFLASH Collaborations

- Osaka City University
- The University of Utah
- NASA Jet Propulsion Laboratory
- SLAC National Accelerator Laboratory
sFLASH in SLAC
sFLASH setup
sFLASH Simulation
sFLASH Simulation

Particle Energy Deposition inside Air (MeV/cm$^3$)
Introduction of Cosmic Rays and Neutrinos Experiments
Summary & Future Plans

sFLASH Simulation

Particle Energy Deposition inside Air for 2 r.l. (MeV/cm²)

Particle Energy Deposition inside Air for 3 r.l. (MeV/cm²)

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UHE Neutrinos Experiment
sFLASH Simulation

Longitudinal distribution

- 15 GeV
- 12.5 GeV
- 5 GeV
- 2.5 GeV

Al₂O₃ (mm)
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3. Summary & Future Plans
Outline: The Distribution of Experiments

- **ANITA (The ANtarctic Impulsive Transient Antenna)** at 32km
- **ARA** at -200m
- **T-510 Radio Emission from Particle Cascades in the Presence of a Magnetic Field**
- **Fluorescence in Air from Showers (sFLASH)**
- **Taiwan Astroparticle Radio wave Observatory for Geo-synchrotron Emission (TAROGE)**

**UHE Neutrinos Experiment**
Taiwan Astroparticle Radiowave Observatory for Geo-synchrotron Emission (TAROGE)
TAROGE at 1200~2000m
Reflection Test of TAROGE

ANITA (The ANtarctic Impulsive Transient Antenna) at 32km
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Transmission test: Transmitter at 5km, 350m separation from the Receivers.

Graphs showing Antenna 1, Antenna 2, Antenna 3, and Antenna 4 with direct and reflected signals.
TAROGE I at He-Ping
A prototype station at 1km height @ Heping
12 Antennas (6 V-pol + 6 H-pol)
Deployed in July 2014
Successful year-round operation for noise survey
6 dual pol. LPDA antennas on 3 towers
No town in FOV / CW insensitive trigger
Longer baseline, time resolution improved
→ Better pointing resolution
Off-grid power
TAROGE 2 and Future
Future Plans

- ANITA-5 (2020): Neutrino & cosmic rays
- SWORD (TBD): Neutrino & cosmic rays
- ARA37 (within 6 years): Neutrino
- TAROGE-10 (within 4 years): Neutrino & cosmic rays
- HCR (>4 years): Neutrino & cosmic rays

Thank you!
The Synoptic Wideband Orbiting Radio Detector (SWORD)

**Figure 1:** The top figure outlines the SWORD mission concept. The UHECR interacts in the atmosphere to produce an extended air shower. The geo-magnetic field separates the protons and electrons in the shower to produce a 30-300 MHz radio illumination area.

**Figure 2:** An example of a simulated $2 \times 10^{20}$ eV cosmic ray induced synchrotron radio impulse after propagation through an ionospheric profile with 14 TECU. The spectrogram of the signal (left) shows the effect of dispersion and birefringence (Equation 1) for a signal detected by a linearly polarized antenna. Waveforms (right) for the bands used in SWORD show the progressively larger amount of

**Figure 4:** The CHIRP satellite consists of a deployable log-periodic dipole antenna that is 4.7 meters in length with 3.7 meter longest dipole element. The antenna is stowed in a 1.5U volume of the 6U CubeSat bus, which contains all the major subsystems needed for the mission.
Potential and Issues

- ANITA-5 (2020): Neutrino & cosmic rays
- SWORD(TBD): cosmic rays
- ARA37 (within 10 years): Neutrino
- TAROGE-10 (within 4 years): Neutrino & cosmic rays
For Further Reading I

A. Author.
*Handbook of Everything.*

S. Someone.
On this and that.
*Journal on This and That.* 2(1):50–100, 2000.