Future All-Sky TeV Gamma-Ray Observatories

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Goals of TeV Astrophysics

- Cosmic Rays
  - Origin of cosmic rays
  - Cosmic particle acceleration
  - Understand astrophysical jets and extreme environments

- Cosmology
  - Measure the extragalactic background light
  - Measure intergalactic magnetic fields (magnetogenesis)

- Search for new physics
  - Dark matter
  - Axion-like particles
  - Violations of Lorentz invariance
Gamma Ray Telescopes

Atmospheric Cherenkov Telescopes
H.E.S.S./VERITAS/MAGIC

- 50 GeV - 100 TeV
- Large Area
- Excellent background rejection
- Small Aperture/Low Duty Cycle

- Study known sources
- Deep surveys of limited regions
- Source morphology (SNRs)
- Fast transients (AGN flares)

EAS Arrays
Milagro/Tibet/ARGO

- 100 GeV - 100 TeV
- Large Area
- Good background rejection
- Large Aperture & Duty Cycle

- Sky survey & monitoring
- Extended Sources
- Transients (GRBs, AGN flares)
- Highest Energies (>10 TeV)
Roles of All-Sky Instrument

• Present
  - Galactic Survey at high energies
  - Extended objects (PWN, Diffuse emission)
  - High mass dark matter (>10 TeV)
  - Extragalactic surveys and transients
  - Multi-Messenger instrument

• Future (with CTA)
  - “Finder” telescope for CTA
  - Extragalactic survey (CTA will survey 1/4 of the sky)
  - Extragalactic transient (AGN, GRBs) detector
  - Multi-messenger instrument
Extensive Air Showers

- γ showers almost purely e-m and relatively compact
- Hadronic showers contain muons (~30/TeV)
- Both have core of energetic particles
- Ground-based VHE telescopes must distinguish protons from photons

F. Schmidt, "CORSIKA Shower Images", http://www.ast.leeds.ac.uk/~fs/showerimages.html
Extensive Air Shower Arrays

- Detect particle that survive to ground level
- Scintillation detector arrays sparsely instrument the ground <2% coverage
- Water detectors (or RPC carpet) can densely sample the shower particles (~50% particles detected)
- Water will also convert gamma rays to electrons/positrons (gamma rays dominate the particles on ground ~6:1)
- Deep water detector (≳4m) can serve as muon detector
Angular and Energy Reconstruction

Primary energy via energy at ground (shower fluctuations dominate resolution ~40%)

Direction via timing (~ns timing yields 0.2°-1° resolution)
Background Rejection

Gamma rays

Protons

30 GeV

70 GeV

230 GeV

20 GeV

70 GeV

270 GeV

300 m
HAWC Sky

HAWC-111 (283 d) + HAWC-250 (105 d)

PRELIMINARY
Extragalactic Gamma Rays

- Active Galaxies (57 detected in VHE band)
  - Extragalactic Background Light
  - Primordial Magnetic Fields
  - Axion-like Particle Searches
- Gamma Ray Bursts (not yet detected from ground)
  - Lorentz Invariance Violation
Extragalactic Background Light

• The sum of all UV, optical, and IR radiation emitted over the history of the universe
• Main contributions from stars and light re-radiated by dust
• EBL is useful tool for probing other physics
  – Axion-like particles
  – UHECR accelerators
  – Intergalactic Magnetic Fields
• Require low threshold to see distant sources

\[ \gamma_{eV} + \gamma_{TeV} \rightarrow e^+ e^- \]

Dwek & Krennrich 2012
Active Galaxies

- Variability detected in ~20% of VHE AGN
- Alert CTA of flaring activity

Mrk 421

Tluczykont, et al. 2007

HAWC 1-day sensitivity
CTA and HAWC

Differential Sensitivity per Quarter Decade

Sensitivity $E^2 \frac{dN}{dE}$ [ergs cm$^{-2}$ s$^{-1}$]

Energy [GeV]

- Crab
- Fermi 5 yr
- H.E.S.S./VERITAS 50 hrs
- HAWC-300 3 yr
- CTA 50 hr
CTA Survey Plans

Survey the Galaxy to 3.8 mCrab (~5x sensitivity of HAWC 5yr)

Survey 1/4 of the sky to 6.5 mCrab ~3x HAWC 5yr

AGNs in CTA ExGal Survey: 144
Sources CTA Gal Plane Survey: 486
Sources in Fermi/LAT Catalog: 416
AGNs detected by IACTs: 52

from R. Ong
CTA and HAWC

• HAWC sensitivity well matched to current generation of IACTs (VERITAS, H.E.S.S., and MAGIC)

• To be useful to CTA we need:
  - ~10x greater sensitivity
  - Ability to detect extragalactic transients (AGN, GRBs)
  - Significantly lower median energy (~300 GeV)
  - Southern hemisphere site

• Is this possible?
Extreme Altitude Array

Radiation Lengths

# of Electromagnetic Particles

$10^{-1}$ $10$ $10^2$ $10^3$ $10^4$ $10^5$

100 GeV

6000m

10 TeV

5600m

Future? 13-18

4100m

100 TeV

2600m

Milagro I

HAWC 3.5

$1 \text{T}$
Extreme Altitude Study

• Assume a 30 x 30 tank array with 3m separation (8100 m$^2$ total area)
• Each tank 1.5m deep x 3m diameter (dense pack)
• Single 10” high QE PMT at bottom looking up
  - 0.25 PE/MeV
  - 0.10 PE/MeV in HAWC
• Trigger on 30 (of 900) tanks
• No noise in simulation
• Test altitudes of 4100m (HAWC), 5200m, 6000m, 6600m
• Gamma rays from 10 GeV to 1 TeV (E$^{-2.3}$ spectrum)
• Protons from 10 GeV to 1 TeV (E$^{-2.7}$ spectrum)
Results: Effective Area

- Physical Area
- Well reconstructed events
Results: Sensitivity

- An array at 6000m is ~5x more sensitive than the same array at 4100m
- >10x area at 100 GeV
- Larger improvement for extragalactic sources
- AGN and GRBs are strength of extreme altitude array
- 5-10x GRB detection capability of HAWC
How High is Possible?

A LUNAR WATER CHERENKOV GAMMA-RAY TELESCOPE

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ABSTRACT

Extension of gamma-ray astronomy to energies above the practical range of the Gamma Ray Observatory (GRO) will require an instrument with an effective area of greater than 10 square meters, exposure times of several weeks, and enough mass to contain gamma-ray-generated electromagnetic showers >5 GeV. A relatively modest water Cherenkov detector located on the moon could meet these criteria and would have some advantages over conventional techniques. A possible detector configuration is discussed.
Cerro Toco (5604m)

Cerro Chanjnator (5610m)

Cerro ?? (5650m)
Concept Studies Underway
Dense pack 1242 tanks

Water tank
w/muon detector

~20,000 m²

Y. Becherini and M. Punch - Linneaus University
LATTES

10,000-20,000 m² of layered detectors
60x30 array

Pb sheet, RPC, water Cherenkov

P. Assis, U. Barres de Almeida, A. Blanco, R. Conceição, A. De Angelis, P. Fonte, L. Lopes, G. Matthiae, M. Pimenta, R. Shellard, B. Tomé
Summary

• Gamma-Ray experimental techniques have made enormous progress in the past 25 years
• Complementarity of all-sky and pointed instruments
• With CTA coming a future all-sky array should have ~10x increase in sensitivity over HAWC
• Extragalactic transient detection requires low threshold, ~few 100 GeV
• Extreme altitude is key
• 5600 meters asl seems feasible
• New detector ideas are under study
Back Up
Extragalactic Survey

[Graph showing number of sources versus log(ν_peak f_peak) [erg cm⁻² s⁻¹] with CTA on-source sensitivity limit, CTA extragalactic survey sensitivity limit, and TeV detected regions indicated.]
Possible Sites
Chajnantor Science Preserve

Cerro Chajnantor
Location of CCAT
S 22° 59’ 8.3”
W 67° 44’ 25.0”
5611 m asl

Cerro ??
S 23° 0’ 28.5”
W 67° 41’ 8.0”
5650 m asl
Gamma-Ray Bursts

• Discovered in 1960’s - Vela satellite
• Most energetic events in the universe
• Detected to $z \sim 9.4$
• $\sim 10^{51}$ ergs released in gamma rays
• Emission highly collimated ($1^\circ$-10$^\circ$)
• Bi-modal duration distribution
  - short duration bursts <2 seconds (binary neutron star mergers)
  - long duration bursts >2 seconds (hypernovae - collapse of massive stars)
GRB Distances

![GRB Distances Chart](http://www.raunvis.hi.is/~pja/GRBsample.html)

**Billions of lyrs**
- 2.2
- 1.9
- 1.3
- 1.0
- 1.5
- 2.0
- 2.2
- 2.4
- 2.7
- 3.0
- 3.5
- 4.0
- 4.5
- 5.0
- 5.5
- 6.0
- 6.5
- 7.0
- 7.5
- 8.0
- 8.5
- 9.0
- 9.5
- 10.0

**Mean and Median Z-values**
- Swift bursts: Mean = 2.24, Median = 1.95
- Pre-Swift bursts: Mean = 1.35, Median = 1.02
Testing Lorentz Invariance

- Many theories of quantum gravity violate Lorentz invariance
- Can be manifest as an energy dependent speed of light
- Gamma ray bursts and AGN flares provide an excellent probe of LIV

\[ v_l \approx c \left( 1 - \xi_1 \frac{E}{M_{QG}} \right) \]

\[ v_q \approx c \left( 1 - \xi_2 \frac{E^2}{M_{QG}^2} \right) \]
GRB 090510  
z=0.903  \ E_{\text{max}} = 31 \ \text{GeV}

PKS 2155-304  
z=0.116  \ E_{\text{max}}=2 \ \text{TeV}

Fermi collaboration, Nature, 2009 v. 462 p331

H.E.S.S. Collaboration, Astroparticle Physics, 2011 v34 p738

July 28, 1996

RICAP, June 2016

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