Viewing the Universe at Very High Energies

VERITAS (Mt. Hopkins, AZ)

Gamma-ray
Particle shower
~ 10 km
Cherenkov light

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Outline

Scientific Motivation

- A “New Astronomy”
- Physicist’s Viewpoint
  - Astrophysical TeV accelerators
    - \(1 \text{ TeV} = 10^{12} \text{ eV}\)
  - Origin of Cosmic Rays, understanding AGN …
  - Probes of new physics, cosmology.

Experimental Technique

The VERITAS Project

- Description, performance.
- Highlights of results from 18 months.
- Science Program, overlap with Fermi Telescope.

Future
A New Astronomy

- Before 1940’s – Astronomy only used visible light.

- New wavebands (radio, IR, X-ray, γ-ray) change our picture of the universe
  - Different spatial scales
  - Different time scales
  - Different emission processes
  - New physics

- Other messengers (cosmic rays, neutrinos, grav. waves)
New Windows & New Messengers

Messengers

- Cosmic Rays
- Neutrinos
- γ-rays

Radio IR O UV X-rays

Log Frequency (Hz)

9 12 15 18 21 24 27 30 33

“THERMAL” UNIVERSE

“Dark” TeV

Active Galactic Nuclei (AGN)

“Dark” TeV Accelerators

PeV ν’s

>10^{19} eV

Particles

Gamma-Ray Bursts (GRBs)

Log Energy (eV)

-6 -3 0 3 6 9 12 15 18 21

HE VHE UHE

“NON-THERMAL” UNIVERSE
The TeV $\gamma$-ray Sky - 1998

3 sources

Mrk421
Mrk501
Crab

Pulsar Nebula
AGN
SNR
Other, UNID
The TeV $\gamma$-ray Sky - 2008

- Shell-type SNR
- Pulsar Wind Nebula
- X-ray Binary
- Unidentified
- AGN

> 60 Sources

- Explosion in number of sources, and a variety of source classes...
- Much more information: imaging, spectra, light curves …

(Almost all) discoveries made by Atmospheric Cherenkov Telescopes
A Wide Variety of Sources …

- **Supernova Remnants**
  - Shocks
  - Fermi Mechanism

- **Pulsars/PWN**
  - NS dynamo
  - Winds

- **HMXBs (microquasars)**
  - Accretion-powered jets, colliding winds, or …?

- **Active Galactic Nuclei**
  - Massive BH
  - Jets

- **Gamma-Ray Bursts**
  - Massive star collapse
  - Int./ext. shocks

- **Dark accelerators**
  - ???
  - … and accelerators
Key Physics Issues

- **SNR**
- **AGN**
- **GRBs**

**Origin of cosmic rays**

**Cosmological \( \gamma \)-ray horizon**

**Tests of Lorentz invariance**

**Cold dark matter (WIMP) searches**

- **Sgr A East SNR**
- **Galactic Center**

**Low E**

**High E**
Origin of Cosmic Rays = SNRs?

Why (VHE) gamma rays?

- Unlike cosmic rays, *not deflected* by interstellar magnetic fields.
- *Tracers* of parent particle populations – those particles accelerated by shocks.

**Accelerated electrons**

\[ \rightarrow \text{VHE } \gamma \text{-rays} \]

Up-scattering of soft photons

**Accelerated protons**

\[ \rightarrow \text{VHE } \gamma \text{-rays} \]

Target interaction, \( \pi^0 \) decay

\[ p \rightarrow \pi^0 \rightarrow \gamma \gamma \]

Target material

There is evidence for SNR acceleration of CRs, but case is far from settled.

SNR Image (RXJ 1713-3946)

Spectral Energy Distribution
Active Galaxies

Active Galactic Nuclei

- High-luminosity extragalactic objects
  - Probe properties of the universe at large distances
- Variable!
- Jets powered by accretion on to supermassive BH

So far, AGN observed in VHE $\gamma$-rays are generally:

- **Blazars**
  - Jets aligned with line of sight
  - Nearby: $z < 0.25$, EBL cutoff.
  - Soft spectrum $\Gamma > 3.0$.

But not all are like this!
Extragalactic Background Light (EBL)

Diffuse extragalactic background light (how much light since recombination?)

- Complements direct measurement in Optical, IR: *difficult*.
- Absorption signature in 50-1000 GeV band for distant sources.
Search for Cold Dark Matter

Hypothesis: DM = WIMPs
• Indirect detection of WIMP annihilation $\rightarrow \gamma, \nu$ etc.

- $\chi + \chi$
- $\nu, \bar{\nu}$
- $\gamma$ continuum
- $\gamma$ lines

Target regions with:
• Favorable DM distributions.
• Large mass/light ratio.

Galactic Halo
Galactic Satellites
Extragalactic Sources

Search for excess components in cosmic rays (Diffusion)
(PAMELA, AMS, GAPS)

Simulated $\gamma$-ray signature in galaxy Taylor & Babul (2005)

Point back to source

Complementary approach to direct detection & LHC.
Experimental Technique
Effective area = light pool size = $10^5 \text{ m}^2$ !!!
Whipple 10m γ-ray Telescope

- The Whipple 10m (1968 - ).
- Pioneered use of Imaging. T. Weekes et al.
- Made first source detections.

gamma ray?  cosmic ray?
Major VHE Telescopes

Multi-messenger Astronomy

- MAGIC
- Fermi
- VERITAS
- HESS
- CANGAROO

(Auger, CR’s)

IceCube, ν’s (2011)
Very Energy Radiation Imaging Telescope Array System (VERITAS)


Detector Design:
- Four 12m telescopes.
- 500 pixel cameras (3.5°).
- Site in southern Az (1300m).

Performance:
- Energy threshold ~ 100 GeV.
- Ang. resolution ~ 4-6’.
- Detect Crab Nebula in ~45s.
Bumps in the Road

VERITAS had three major road-blocks:

1998 Project formally proposed
2000 Ranked highly in Decadal Survey
2001 First Major Review (Ritz)

Smithsonian forced to reduce funding

2003 Second Major Review (Blandford)

Unable to secure site on Mt. Hopkins
Invited to Kitt Peak (NSF/NOAO)

2004 Construction starts

2005 Telescope 1 operational at basecamp

2006 Telescope 2 & 3 at Whipple basecamp.

2007 4 Telescope array fully operational!

2008 VERITAS sited permanently at basecamp.
VERITAS: Mt. Hopkins, AZ

U.S.:
- Adler Planetarium
- Argonne National Lab
- Barnard College
- DePauw Univ.
- Grinnell College
- Iowa State Univ.
- Purdue Univ.
- Smithsonian
- Univ. of California, Los Angeles
- Univ. of California, Santa Cruz
- Univ. of Chicago
- Univ. of Delaware
- Univ. of Iowa
- Univ. of Massachusetts
- Univ. of Utah
- Washington Univ., St. Louis

Canada:
- McGill Univ.

Ireland:
- Cork Inst. Tech.

U.K.:
- Nat. Univ. Ireland, Galway
- Univ. College Dublin

+ ~25 Associate Members
Telescope Layout

- T1: Jan 2005
- T2: Spring 2006
- T3: Fall 2006
- T4: Spring 2007
T1 Jan 2005

T2 Spring 2006

T3 Fall 2006

T4 Spring 2007

7km

108m

82m

85m

35m
Relocating T1

Sensitivity Improvement ~ 20%
A VERITAS Telescope

12m reflector, f1.0 optics

350 Mirror Facets

500 pixel Camera
VERITAS Data Acquisition

- PMTs digitized with 500 MHz sampling FADCs
  - 24 samples/channel.
  - <6% deadtime @ 250 Hz.

Telescopes/cameras/electronics meet all design specifications.
Veritas-4 at the Whipple Observatory

Four-Telescope Event

Core position on ground.

Arrival Direction in Sky

T1, T2, T3, T4
Crab Nebula – Now a Calibration!

VERITAS Sensitivity:
- 1 Crab: 45s (5σ)
- 5% Crab: ~2.5 hr
- 1% Crab: ~40 hrs

Angular resolution 3’-6’
Pointing accuracy < 75”

Energy spectrum
VERITAS First-Year Results

- Discovery of XRB LSI +61
- Discovery of SNR IC443
- Discovery of SNR Cassiopeia A
- Discovery of Blazar 1ES1218+30, z=0.182, 2nd most distant VHE source
- Discovery of Blazar W Comae, z = 0.102
- Discovery of Blazar 1ES 0806, z = 0.138
- Discovery of Blazar 3C 66A, z = 0.444, Most distant source?
IC443: The Case For Hadronic Emission?

- Overlap with CO indicating molecular cloud along line of sight.
- Maser emission suggests SNR shock interacting with cloud.
- TeV emission could be CR-induced pion production in cloud (1,2)

New Blazars with VERITAS

- **W Comae**: VERITAS discovery
  - 2 flares, 1 taken in moonlight.
  - First IBL discovered at VHE.
  - Simultaneous Swift data.

Two AGN in the same field.

*Astrophysical Journal, 684, L73, 2008*

Light curve

Broad-band SED, EC preferred.
New Blazars with VERITAS II

- 3C66A
  - Distant? Z= 0.444 based on a single emission line (TeV spectrum raises questions).
  - VERITAS excludes 3C66B (in 2008) at 4.3σ.

Controversy:
Blazar
or
Radio
galaxy?

MAGIC claims 3C66B (@85% CL) in 2007

Very soft spectrum
Γ = 4.1 +/- 0.4 +/- 0.6
If z =0.444, Γ_{int} = 1.1
Via Franceschini et al. 2008

Also, significant MWL paper with Fermi, Swift, XMM, optical, radio.
Dark Matter Search: Dwarf Galaxies

Recent VERITAS observations:
Draco, Ursa Minor, Willman I

\[ \langle \sigma v \rangle: \text{Thermal average of product} \]
\[ \sigma: \text{WIMP self-annihilation x-sec} \]
\[ v: \text{WIMP velocity} \]

Future Constraint by LHC

\[ M_\chi [\text{GeV}] \]

Whipple 10m
Ursa Minor constraint

VERITAS (and 15 hr data)
Willman I constraints
derived from
Strigari et al. 2007

Minimal Supersymmetric extensions to Standard Model (MSSM) allowed by WMAP
What’s next for VERITAS?

LOTS!

• **New Results**: to be announced this summer.

• **Observing**: we are in 2nd year of 5+ year program.

• **Fermi Gama-Ray Space Telescope** overlap.

• **Spectra and modelling**: source mechanisms.

• **MWL studies**: radio, optical, X-ray, γ-ray.

• **Upgrade possibilities**: e.g. new cameras, triggers.

• …
VERITAS Sky Survey

SNR/PWN

TeV Unidentified

EGRET (GeV)

X-ray binaries

Other possible source types:
- star clusters/star-forming regions, Wolf-Rayet stars
- or the completely unexpected!

- 2 year project, covering 150 deg$^2$.
- Ambitious---originally intended a larger region, but getting enough time is challenging (region best visible in July/August monsoon season).
- 150 hrs data taken so far, results this summer.
LAT images the sky one photon at a time: \( \gamma \)-ray converts in LAT to an electron and a positron; direction and energy of these particles tell us the direction and energy of the photon.
Fermi-LAT science objectives

> 2000 AGNs
  blazars and radiogal = f(θ,z)
  evolution z < 5
  Sag A*

Possibilities
  starburst galaxies
  galaxy clusters
  measure EBL
  unIDs

10-50 GRB/year
  GeV afterglow
  spectra to high energy

Dark Matter
  neutralino lines
  sub-halo clumps

γ-ray binaries
  Pulsar winds
  μ-quasar jets

Cosmic rays and clouds
  acceleration in Supernova remnants
  OB associations
  propagation (Milky Way, M31, LMC, SMC)
  Interstellar mass tracers in galaxies

Pulsars
  emission from radio and X-ray pulsars
  blind searches for new Gemingas
  magnetospheric physics
  pulsar wind nebulae
Launch from Cape Canaveral Air Station
11 June 2008 at 12:05PM EDT.
First Light  FGST-LAT

• ~4-day First Light exposure, June 30 – July 3, 2008.
• Orthographic projection.
• Comparable to EGRET on CGRO!
Vela (2 cycles, 89 ms period)
Fermi $\gamma$-ray Sky  (Feb 2009)
VERITAS Source Catalog (18 mo)

New Source

Mrk 421
1ES 0806
1ES 1218
+90°
W Comae

Mrk 501
3C66A
M87

IC443
-180°
Crab

IC 443
1ES 1959
Cas A
MGRO1908
1ES 2344

Crab

VERITAS Discovery of VHE Gamma-Ray Emission from BL Lac object RGB J0710+591

ATel 18108: Rave One (CTA) for the VERITAS Collaboration

Source: The Astronomer’s Telegram

The VERITAS collaboration reports the discovery of very high energy (VHE; E > 100 GeV) gamma-ray emission from the BL Lac object RGB J0710+591 (z = 0.128). This new VHE source was observed for 18 hours per night over three nights between 3 January and 23 February 2020 (UT) with the VERITAS array of Cherenkov telescopes. Preliminary analysis of these data yields a detection of ~150 gamma-rays from RGB J0710+591, corresponding to a significance of ~5 standard deviations. The VHE flux is ~1.0% of the Crab above 200 GeV, and there is no evidence of this variability. VERITAS will continue to observe RGB J0710+591 and contemporaneous multi-wavelength observations of this blazar are encouraged.
Next 5-10 years will be exciting period for this field:

VERITAS will survey the northern TeV sky with great sensitivity, complementing:

- Fermi-LAT (GeV, in space)
- HESS (TeV, S. Hemisphere)
- IceCube (ν, South Pole)
- Auger S (UHECR, S. Hemisphere)

Farther in the future:

- Astrophysics at GeV & TeV energies with large km² Cherenkov Telescope arrays.
• Populations of fainter sources we have yet to probe.
• TeV source confusion may be starting to be an issue.
  • very deep observations to get morphology, disentangle sources
• Need larger source populations to get away from source idiosyncrasies.
• Next few years with Fermi may help to answer questions
  • …but not completely.
  • …and we will have many new sources!
AGIS (Advanced Gamma Imaging System)

Large (1 km²) array.
- ~50-75 telescopes, aperture 8-20m.
- $100-150M class observatory.

Much more sensitive than FGST/VERITAS.
APS White Paper study, collaboration formed.

CTA (Europe) – considerable momentum.
“Ground-Based Gamma Ray Astronomy, Towards the future”, Oct. 20-21 2005, Malibu, CA (UCLA)

“Ground-Based Gamma Ray Astronomy, Towards the future”, May 11-12 2006, Santa Fe, NM (LANL)


Collaboration meeting, June 27-28 2008, UCLA, Formation of AGIS collaboration

Institutions:

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Wide-Field Schwarzschild-Coudet Telescope
Summary

• HE $\gamma$-rays provide unique tests of the limits of physical laws. Probe astrophysics in regimes not yet explored. Possibility for discovery of physics beyond our standard models.

• Exciting discoveries of many, unexpected sources of VHE gamma-rays. But still, most of the sky remains unexplored.

  → VERITAS and Fermi are now both operational and getting exciting results.

• New Astronomy of TeV $\gamma$-rays (and neutrinos, grav. waves) should reveal many surprises over the next 10 years.

“The real voyage of discovery consists, not in seeking new landscapes, but in having new eyes.”

Marcel Proust (1871-1922)