Viewing the Universe with $\gamma$-ray Eyes

VERITAS (Mt. Hopkins, AZ)

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Outline

Scientific Motivation

- A “New Astronomy”
- Physicist’s Viewpoint
  - Astrophysical Terra-eV accelerators
    - $1 \text{ TeV} = 10^{12} \text{ eV}$
    - Probes of new physics (e.g. dark matter)

Experimental Technique

The VERITAS Project

- Description, performance.
- Highlights of results from 18 months.
- Fermi Gamma-ray Space Telescope (FGST)

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 too! (cosmic rays, neutrinos, & gravitational waves).

Here we focus on TeV γ-rays.
New Windows & New Messengers

Messengers

Radio  IR  O  UV  X-rays

Cosmic Rays
Neutrinos
γ-rays

Log Frequency (Hz)

“THERMAL” UNIVERSE

NON-THERMAL UNIVERSE

Log Energy (eV)

Gamma-Ray Bursts (GRBs)
Active Galactic Nuclei (AGN)
“Dark” TeV Accelerators
PeV ν’s

>10^{19} eV Particles
But, do TeV $\gamma$-ray sources even exist?

YES!
The TeV $\gamma$-ray Sky - 1998

3 sources

- Mrk421
- Mrk501
- Crab

- Pulsar Nebula
- AGN
- SNR
- Other, UNID
The TeV γ-ray Sky - 2003

12 sources

- Mrk421
- H1426
- M87
- 1ES1959
- Mrk501
- RXJ 1713
- GC
- 1ES 2344
- Cas A
- TeV 2032
- PKS 2155

- Pulsar Nebula
- AGN
- SNR
- Other, UNID
The TeV $\gamma$-ray Sky - 2009

- Explosion in number of sources.

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

Supernova Remnants
- Supernova Remnants
- Shocks
- Fermi Mechanism

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

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

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

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

Dark accelerators…

… and accelerators.
Key Physics Issues

- SNR
- Origin of cosmic rays
- AGN
- Cosmological \( \gamma \)-ray horizon
- GRBs
- Tests of Lorentz invariance
- Sgr A East SNR
- Galactic Center
- Cold dark matter (WIMP) searches
Supernova Remnants: Origin of CR’s?

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 → VHE γ-rays
Up-scattering of soft photons

Accelerated protons → VHE γ-rays
Target interaction, π⁰ decay

Inverse Compton Scattering

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

SNR Image (RXJ 1713-3946)
Spectral Energy Distribution
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.

Red shifted stellar light
Red shifted dust light
Search for Cold Dark Matter

Hypothesis:
- Cold dark matter – decays or annihilates to give $\gamma$ signal.

Target regions with:
- Favorable DM distributions.

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

- The Whipple 10m (1968 - ).
- Pioneered use of imaging: T. Weekes et al.
- Made first source detections Crab in 70 hours of observing.

gamma ray?  

Camera

cosmic ray?
Stereoscopy: Telescope Arrays
Major VHE Telescopes

Multi-messenger Astronomy

MAGIC
VERITAS
HESS
IceCube, ν’s (2011)
CANGAROO

Fermi

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 roadblocks:

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.
- Nat. Univ. Ireland, Galway
- Univ. College Dublin

**U.K.:**
- Leeds Univ.

+ ~25 Associate Members
Telescope Layout

T1 Jan 2005
T2 Spring 2006
T3 Fall 2006
T4 Spring 2007
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
Four-Telescope Event

Core position on ground.

Arrival Direction in Sky
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

- **XRB LSI +61**
- **Discovery of SNR IC 443**
- **SNR Cassiopeia A**
- **M87 Radio Galaxy**
- **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?
Supernova Remnant IC443


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.

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.


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

- **3C66A**
  - Distant AGN $z = 0.444$.
  - VERITAS excludes 3C66B (in 2008) at $4.3\sigma$.

**Controversy:**
Blazar or Radio galaxy?

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

**Very soft spectrum**
$\Gamma = 4.1 +/\ - 0.4 +/\ - 0.6$

Dark Matter Search: Dwarf Galaxies

Recent VERITAS observations:
Draco, Ursa Minor, Willman I

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

\[
\sigma: \text{WIMP self-annihilation } x-sec
\]

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 2\textsuperscript{nd} year of 5+ year program.
- **Fermi Gama-Ray Space Telescope** overlap.
- **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 moonsoon 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*

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

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

Possibilities
starburst galaxies
galaxy clusters
measure EBL
unIDs

Dark Matter
neutralino lines
sub-halo clumps

Pulsars
emission from radio and X-ray pulsars
blind searches for new Geminias
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)
The Pulsing $\gamma$-ray Sky

Fermi Pulsar Detections

- New pulsars discovered in a blind search
- Millisecond radio pulsars
- Young radio pulsars
- Pulsars seen by Compton Observatory EGRET instrument

Pulses at 1/10th true rate
Fermi $\gamma$-ray Sky (Feb 2009)
VERITAS Source Catalog (18 mo)
Next 5-10 years will be exciting period for this field:

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

- Fermi GST (GeV, in space)
- HESS (TeV, S. Hemisphere)
- IceCube ($\nu$, South Pole)

Farther in the future:

- Astrophysics at GeV & TeV energies with large km$^2$ Cherenkov Telescope arrays.
The Next Generation

- 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.

Transition to Fermi Regime (GRBs, etc.)
Spectral cutoffs (acceleration mechanisms)
AGIS
(Advanced Gamma-ray Imaging System)

Institutions:

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Summary

• VHE $\gamma$-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)