The Mysterious Gamma-Ray Universe

VERITAS

Cas A

Sgr A*

VERITAS

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Outline

1. The Gamma-Ray Universe:
   - A new Astronomical window
   - Relevant Physics issues

2. Atmospheric Cherenkov Technique

3. VERITAS $\gamma$-ray Telescope:
   - Design & performance
   - Some recent results

4. The Future:
   - Cherenkov Telescope Array (CTA)
Spectrum of Light

Energy (eV) | 1 | $10^3$ | $10^6$ | $10^9$ | $10^{12}$
A New Astronomy

- Before 1940’s – Astronomy only used **visible light**.
- New wavebands (radio, IR, X-ray, $\gamma$-ray) change our picture of the universe.
- Other messengers too: neutrinos & grav. waves.

![Crab Nebula](image)

- **Radio**
- **Optical**
- **X-rays**

**Crab Pulsar (X-rays)**

**Crab Nebula**
Gamma Rays

With gamma rays, we:

- Study extreme processes in the cosmos not visible to the naked eye.
- Probe distance scales much smaller than the size of the atom.
- Study fundamental physics at a much earlier time in the Universe.
Energy Scale

1 GeV = $10^9$ eV

1 TeV = $10^{12}$ eV

(Optical light ~ 1 eV)

Q: Do astrophysical sources of GeV/TeV $\gamma$-rays even exist?
The TeV $\gamma$-ray Sky - 1999

4 sources

Source Types
- Plerion PWN
- HBL IBL FRI FSRQ LBL

Mrk421
Mrk501
Crab

1ES 2344
The TeV $\gamma$-ray Sky - 2010

13 sources

Source Types

- Plerion PWN
- HBL IBL FRI FSRQ LBL
- Shell
- MQS Cat. Var. UNID
- Other BIN WR
The TeV $\gamma$-ray Sky - 2012

~120 sources

- Explosion in number of sources and variety of source classes.
- High-quality information: imaging, spectra, light curves.

Most discoveries made by Atmospheric Cherenkov Telescopes
Science of VHE $\gamma$-ray Astrophysics

- Pulsars
- $\mu$Quasars
- Starbursts
- SNRs/CRs
- AGN
- UnIDs
- Dark Accel.
- Dark Matter
- Cosmological Fields
- PBHs, QGr
- GRBs

Exploring the non-thermal Universe

Probing new Physics at GeV/TeV scale
Key Physics Issues

- Origin of cosmic rays
- Cosmological $\gamma$-ray horizon
- Tests of Lorentz invariance
- Cold dark matter (WIMP) searches

- SNR
- AGN
- GRBs
- Galactic Center

- Sgr A East SNR
- Sgr A*
- TeV cog (prelim.)
- Galactic Center
Origin of Cosmic Rays

90 year old mystery!
- Enormous E range
- Mostly charged particles
- E density ~ 1 eV/cm³

Neutral messengers: $\gamma$, $\nu$

are required to directly observe cosmic accelerators.

Diffuse, all particle spectrum
Supernova Remnants (SNR’s)

- Collapse of massive star or detonation of white dwarf.
- Outer layers ejected with $v \sim 3 \times 10^3$ km/s. Shell expands and shock front forms.
- Acceleration of particles via “canonical” Fermi process – or diffusive shock acceleration.
- In $\sim 10^4$ yrs, blast wave decelerates and dissipates.
- SNRs can supply and replenish CR’s if $\varepsilon \sim 5\%-10\%$.
- Electrons or Protons?
Cold Dark Matter

There is overwhelming astrophysical evidence for dark matter, from e.g.

- rotation curves of spiral galaxies,
- colliding clusters & gravitational lensing, &
- cosmological measurements.

Cosmology, in particular, points towards DM being:

- non-baryonic
- non-relativistic  \[\rightarrow\text{Cold dark matter (CDM)}\]

Numerous CDM candidates exist:

- Primordial BH's
- Axions
- Weakly interacting massive particles (WIMPs).

“**WIMP miracle**”: present relic density is consistent with expected for a weakly interacting particle & new particle physics is required at the weak scale (EWSB).
DM Detection: Complementary Approaches

Produce DM particle in accelerators

Direct Detection

$\sigma_{\text{int}}$

LHC at CERN

Astrophysical Indirect Detection

Sextens dwarf galaxy

Annihilation ($\sigma_A$)

$\chi\chi \rightarrow \gamma's, \nu's,\text{ anti-matter}$

Xenon1T Detector

VERITAS

GAPS
DM Detection via $\gamma$-rays

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

“Universal” Spectrum

Galactic Halo

Dwarf Satellites

Extragalactic Sources

HESS, Whipple, & Cangaroo detected a strong source at Gal. Center

$\Rightarrow$ Is it dark matter?
Atmospheric Cherenkov Technique
Effective area = light pool size = $10^5$ m$^2$ !!!
Whipple 10m $\gamma$-ray Telescope

- Used Imaging Technique.
- Made first source detections. (Crab Nebula in $\sim$90 hours)

$\gamma$-ray?  cosmic ray?
Large Area Cherenkov Telescopes

- 1990’s: Developed telescopes to sample entire light pool.
- Large array of heliostat mirrors.
- STACEE (NM), Solar 2 (CA), CELESTE (France)
Solar-2 Cherenkov Telescope
Major VHE Telescopes

- Fermi
- MAGIC
- VERITAS
- HESS
- CANGAROO III
- IceCube, ν's
- IceCube
VERITAS
\(\gamma\)-ray Telescope
VERITAS

Collaboration of ~100 scientists. 23 Institutions in five countries.

Detector Design:
• Four 12m telescopes.
• 500 pixel cameras (3.5°).
• Site: south Az, USA (1300m).

Performance:
• Energy threshold ~ 100 GeV.
• Ang. resolution ~ 4-6’.
• 1% Crab sensitivity (30 hrs).

Very Energy Radiation Imaging Telescope Array System (VERITAS)
A VERITAS Telescope

12m reflector, f1.0 optics

350 Mirror Facets

500 pixel Camera
Working @ VERITAS

- VERITAS is a collaboration of ~100 scientists, evenly distributed between faculty, postdocs, grad. students.

- Typical grad. student time is ~4 yrs of research work on VERITAS.

- All members in my group typically spent more time at the experiment — excellent hands-on experience.

- We build our own hardware (cameras, electronics, etc.) and all of our own software (C++ code) for analyzing the data.

- A lot of the work is done in a distributed manner – via Wiki pages, e-mail lists and frequent weekly telecons.
Latest VERITAS Results

Dark Matter

Galactic Sources:
Supernova Remnants: Tycho
Crab Pulsar
VERITAS Sky Map (2011)

40+ sources covering 8 source classes
At least 17 sources are likely Galactic (SNRs, PWNe, Binaries, UnIds, Pulsars)

http://tevcat.uchicago.edu
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http://tevcat.uchicago.edu
VERITAS DM Searches

Galactic Center (brand new!)

Strong detection by VERITAS, but interpretation is still unclear; strong astrophysical source present.

Dwarf Spheroidal Galaxies


Limits, based on moderate observations, do not yet rule out any models.
VERITAS Supernova Remnants

Cas A
- Age = 300y
- D = 3.4 kpc

Tycho
- Age = 440y
- D = 2-5 kpc

IC 443
- Age ~ 30ky
- D ~ 0.8kpc

G106.3+2.7
- Age ~ 10ky
- D ~ 0.8 kpc

Boomerang

VER J2019+407
- Age ~ 13ky
- D ~ 1.4 kpc

γ-Cygni
Tycho’s SNR: VERITAS Discovery

- Historical Type 1a SN of 1572
- X-ray morphology argued for hadronic acceleration (Warren et al. 2005)
- VERITAS discovery in 2010 with 68 hrs
- Consistent with leptonic or hadronic models
- Combination of VERITAS + Fermi argue for hadronic acceleration
Crab

Crab Nebula and Pulsar

• Remnant from historical SN in 1054.
• One of the most energetic pulsars and brightest γ-ray pulsars.
• Nebula is the brightest, steady VHE source.

γ-ray observations of Pulsar

• **Fermi-LAT (first EGRET):** exquisite measurements around spectral break near few GeV.
• **MAGIC:** detection at 25 GeV and hint at 60 GeV.
• Numerous, constraining limits from many VHE experiments.
• 30-year effort to detect at VHE.
Crab Pulsar at HE and VHE

MAGIC Result at 25 GeV (Aliu et al., 2008)

- Special trigger to lower $E_{th}$.
- Similar pulse profile to EGRET.
- Exponential $E_{\text{cutoff}} \sim 18$ GeV.
- Rule out polar cap model.

Conventional view:

- Spectral break is described by exponential cut off; i.e. there is a single component.
- Most-favored $\gamma$-ray production mechanism is curvature radiation.
- Emission come from outer regions $>6$ stellar radii. Outer-gap or slot-gap models favored.
VERITAS Result: Detection!

Statistical significance of pulsed signal: H-Test value of 50, i.e. $6.0\sigma$.

E. Aliu et al., Published in Science (2011)
The New Picture of the Crab Pulsar

- First detection of a pulsar above 100 GeV – new astrophysics
- VERITAS detection → emission region > 10 stellar radii.
- Narrowing of pulses → tapered acceleration region?
- Competitive limits on LIV – stay tuned.

NSF Press release:
The Future
Cherenkov Telescope Array

- Factor of ten more sensitive than VERITAS.
- Two sites: South (3km x 3km), North (1km x 1km).
- 40-80 Telescopes per site.
Cherenkov Telescope Array

One observatory with two sites for all-sky coverage operated by one consortium

Two candidate sites in N. Arizona
Coconino, Yavapai Counties
Cherenkov Telescope Array

Exploring the cutoff regime of cosmic accelerators

Hi-z AGN, GRBs, pulsars, dark matter

Population studies, extended sources, variability, precision TeV astronomy
Summary

- VHE $\gamma$-rays probe astrophysics of TeV particle acceleration in the cosmos, as well as probing for new physics beyond the standard model.

- Among the key scientific questions being attacked are the origin of cosmic rays and the nature of dark matter.

- The imaging atmospheric Cherenkov technique allows for sensitive telescopes with good angular & energy resolution.

- VERITAS is the world’s best VHE telescope and producing numerous exciting results; the on-going upgrade will further improve sensitivity. A future experiment, CTA, would achieve an order of magnitude further improvement.

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

Marcel Proust (1871-1922)