Particle Astrophysics at the TeV Scale

VERITAS

Gamma-ray
Particle shower
Cherenkov light
~ 10 km

PSF

Dark Matter Hadronization Coalescence

Rene A. Ong
Colloquium @ Columbia Univ.
28 Feb 2011
This is (only) my second sabbatical; first was U. Michigan in 2005.

Both were marked by:

- wonderful hospitality,
- very stimulating research environment, and
- being able to get a lot done!

<table>
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<th>YEAR</th>
<th>LOCATION</th>
<th>Average</th>
<th>Actual</th>
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<td>2005</td>
<td>Ann Arbor, MI</td>
<td>107 cm</td>
<td>187 cm</td>
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<tr>
<td>2010</td>
<td>New York, NY</td>
<td>68 cm</td>
<td>142 cm (to date!)</td>
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The (Non-Thermal) TeV Universe:
  - Observed sources & relevant astrophysics

Two Key Scientific Questions:
  - Astrophysical particle acceleration → origin of cosmic rays
  - Physics beyond the standard model → dark matter

VERITAS γ-ray Telescope:
  - Design & performance
  - Latest results on these two questions

Future Experiments:
  - GAPS Balloon Instrument to study dark matter
    (Cherenkov Telescope Array)
New Windows, New Messengers

**Messengers**

- CR’s
- Neutrinos
- VERITAS
- GAPS

**Log Frequency (Hz)**
- Radio
- IR
- O
- UV
- X-rays
- γ-rays

**Log Energy (eV)**

- "THERMAL" UNIVERSE
- NON-THERMAL UNIVERSE

**Particles**
- HE
- VHE
- UHE
- >10^{19} eV

**Sources**
- Gamma-Ray Bursts (GRBs)
- Active Galactic Nuclei (AGN)
- "Dark" TeV Accelerators
- PeV ν’s

**Accelerators**
- "Dark" TeV Accelerators

**TeV Accelerators**
- "Dark" TeV Accelerators

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The TeV $\gamma$-ray Sky - 1999

4 sources

Source Types

- Plerion PWN
- HBL IBL FRI FSRQ LBL

Mrk421
Mrk501
1ES 2344
Crab
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

Mrk421, M87, H1426, GC, 1ES 1959, Mrk501, H1426, TV 2032, Cas A, Mrk501, 1ES 2344, 1ES 1959, BL Lac, RXJ 1713, Crab
The TeV $\gamma$-ray Sky - 2011

~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
“Who Ordered Them?”
A Wide Variety of Sources …

Supernova Remnants
- Shocks
- Fermi mechanism

Pulsars/PWN
- NS dynamo
- Winds

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

“Dark accelerators”

GALACTIC

Active Galactic Nuclei

Gamma-Ray Bursts
- Massive star collapse
- Relativistic shocks

Starburst Galaxies
- Star forming activity
- HE Cosmic rays

EXTRA-GALACTIC
Key Physics Issues

- Origin of cosmic rays
- Cosmological $\gamma$-ray horizon
- Tests of Lorentz invariance
- Cold dark matter (WIMP) searches
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; detonation of white dwarf.
- Outer layers ejected with \( v \approx 3 \times 10^3 \) km/s.
- Shell expands and shock front forms as it sweeps up material from ISM.
- Acceleration of particles via “canonical” Fermi process.
- In \( \sim 10^4 \) yrs, blast wave deccelerates and dissipates.
- Can supply and replenish CR’s if \( \varepsilon \approx 5\% \).
Electrons or Protons?

TeV $\gamma$-rays are:
- Not deflected by interstellar magnetic fields.
- Tracers of parent particle populations – those particles accelerated by shocks.

But both electrons and protons produce $\gamma$-rays.

Accelerated electrons $\rightarrow$ TeV $\gamma$-rays
Accelerated protons $\rightarrow$ TeV $\gamma$-rays

Up-scattering of soft photons
Target interaction, $\pi^0$ decay

There is now evidence for SNR acceleration of CRs, but the case is not yet ironclad.
Cold Dark Matter

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

- rotation curves of spiral galaxies,
- velocity distributions in galaxy clusters,
- colliding clusters & gravitational lensing
- cosmological measurements …

Cosmology, in particular, points towards DM being:

- non-baryonic
- non-relativistic

Cold dark matter (CDM)

Numerous CDM candidates exist:

- Primordial BH’s – possible, but production mech. not know.
- Axions – motivated by particle physics; searches underway.
- 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
  - LHC at CERN
- Direct Detection
  - Xenon1T Detector
- Astrophysical Indirect Detection
  - Sextens dwarf galaxy
- Annihilation ($\sigma_A$)
  - $\chi\chi \rightarrow \gamma$'s, $\nu$'s, anti-matter
- VERITAS
- GAPS
Indirect Detection

Telescopes

VERITAS, HESS, Fermi …

ν

IceCube

Cosmic Ray Expts

e⁻

ATIC, Fermi …

e⁺
Pamela, AMS

W⁺/Z/H/q

W⁻/Z/h/q

χ

χ

χ

WIMP Annihilation (e.g. GC)

d

p

GAPS

decreasing background
DM Detection via $\gamma$-rays

Target regions with:

- Favorable DM distributions.
- Large mass/light ratio.

Simulated $\gamma$-ray signal
Taylor & Babul (2005)
DM Detection via $\gamma$-rays

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

"Universal" Spectrum

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

→ Is it dark matter?
DM Detection via anti-Deuterons

Unlike anti-protons, anti-deuteron secondaries are severely suppressed.

Primary Component (DM):
\[ \chi \chi \rightarrow \gamma, p, d \]

Secondary Component:
\[ pA \rightarrow \bar{d}X \text{ [via } p(pn)n] \]

where \( A = p, \text{ He} \)

Anti-deuterons provide extremely clean signature, but low fluxes result in a daunting experimental challenge!
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 in southern Az (1300m).

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

Very Energy Radiation Imaging Telescope Array System (VERITAS)
Multi-messenger Astronomy

Major VHE Telescopes

- MAGIC
- Fermi
- VERITAS
- HESS
- CANGAROO
- IceCube, ν’s
- (Auger, CR’s)

IceCube
VERITAS @ Mt. Hopkins, AZ

U.S. et al. 2006
Adler Planetarium
Argonne Nat. Lab
Barnard College
DePauw Univ.
Grinnell College
Iowa St. Univ.
Purdue Univ.
SAO

UCLA
UCSC
U. of Chicago
U. of Delaware
U. of Iowa
U. of Minnesota
U. of Utah
Washington U.

Canada
McGill Univ.

U.K.
Leeds Univ.

Ireland
Cork Inst. Tech.
Galway-Mayo Inst.
N.U.I. Galway
Univ. College Dublin

Non-Affiliated Members
DESY/Potsdam
Penn State U.

+ 35 Associate Members
Theorists, MWL partners,
IceCube, Fermi, Swift, etc.
From my talk back in 2005 ...
A VERITAS Telescope

12m reflector, f1.0 optics

350 Mirror Facets

500 pixel Camera
Four-Telescope Event

Core position on ground.

Arrival Direction in Sky.
Observation Strategy

Observing Proposals (50%)
- Science WG’s & TAC

Discretionary (10%)
- ToO’s, GRBs
- Higher risk sources

Key Science Projects (40%)
- BLAZARS
- Dark Matter
- Cygnus Sky Survey (2007-9)
- SNRs/PWN

- 850 hours/year Dark Time + 20% Moonlight (= 1000 hours total).
- > 95% Data taken with all four telescopes operational.
VERITAS Results
Cygnus Arm Sky Survey

Cygnus: rich region of SNR’s, PWN, binaries, GeV sources
VERITAS Sky Survey: Strategy

EXPOSURE MAP

Made possible by good VERITAS off-axis sensitivity
- Survey covered region $67^\circ < l < 82^\circ$, $-1^\circ < b < 4^\circ$
- Over 2 year period: ~112 hours in base survey, ~100 hours follow-up.
- ~6 hrs equivalent exposure at every location (before follow-up).

Most sensitive N. Hemisphere survey ever done at TeV energies.
VER J2019+407 may indicate:

- New TeV source
- TeV J2032+4130
  - known source, perhaps associated with pulsar.

Interaction of SNR shell with HI shell \(\rightarrow\) evidence for acceleration of protons.
(Leptonic model possible too).
Region 2: “Cisne”

- Targeted observations followed survey data.

- Motivation and analysis done by Ester Aliu (Barnard postdoc).

- Results to be released soon.
Targeted Discovery: SNR IC443

- Overlap with CO indicating molecular cloud along line of sight.
- Maser emission suggests SNR shock interacting with cloud.
- TeV emission could be from CR-induced pion-production.

Future Deep Observations of IC 443

Upgraded VERITAS Detector

Existing data (20 hours)

Simulated – 100 hours, assuming the emission maps CO
Dark Matter

Results & Future Prospects
VERITAS Dark Matter Program

Because of large uncertainties (WIMP mass, $\sigma$, astrophysical flux), VERITAS observing strategy targets a variety of potential sources.

<table>
<thead>
<tr>
<th>Target</th>
<th>Advantages</th>
<th>Disadvantages</th>
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<td>Galactic Center</td>
<td>- Close by</td>
<td>- Many astrophysical backgrounds</td>
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<td>- Huge amount of DM</td>
<td>- Big uncertainty in the DM distribution</td>
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<td>Dwarf spheroidal galaxies</td>
<td>- DM dominated</td>
<td>- May be beyond reach of current instrument sensitivity</td>
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<tr>
<td></td>
<td>- Clear of astrophysical backgrounds</td>
<td>- Can be tidally disrupted: uncertainty in the DM distribution.</td>
</tr>
<tr>
<td>Globular clusters</td>
<td>- Very close</td>
<td>- Not DM dominated</td>
</tr>
<tr>
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</tr>
<tr>
<td></td>
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<td>- Interplay of baryons with DM not well known</td>
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<td>Clusters of galaxies</td>
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There have been no detections to date.
VERITAS DM Searches

Galactic Center
(brand new!)

Dwarf Spheroidal Galaxies


Strong detection by VERITAS, but interpretation is still unclear.

Limits, based on moderate observations, do not yet rule out any models.
The GAPS Experiment

Collaboration meeting, UCB May 2010

(+ LLNL, Univ. of Latvia)

GAPS Detection Technique

- Conventional method of magnetic mass spectrometer is not optimal for GAPS. (Very large magnets with thin detector materials are needed for a deep survey).

Detection principle was verified and high X-ray yield was shown in accelerator tests (KEK antiproton beam, ’04 - ’05).

1. Once $\bar{D}$ is slowed down and stopped in the target,
2. an excited exotic atom is formed,
3. which de-excites with emitting X-rays,
4. and annihilates with producing a pion shower.

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GAPS Concept

GAPS consists of two detectors (acceptance ~2.7 m²sr):

Si(Li) Detector (target and tracker):
- Si(Li) tracker: 13 layers of Si(Li) wafers
- relatively low Z material
- good X-ray resolution
- circular modules segmented into 8 strips
  \[ \rightarrow \] 3D particle tracking
- 270 per layer (total: ~3500)
- timing: ~50 ns
- dual channel electronics
  5-200 keV: X-rays (resolution:~2 keV)
  0.1-200 MeV: charged particle

Time of flight and anticoincidence shield:
- plastic scintillator with PMTs surrounds tracker
- track charged particles, dE/dX
- velocity measurement
- anticoincidence for charged particles

LD Balloon flight in 2015?
Prototype Experiment

Prototype GAPS (pGAPS) goals:

- demonstrate stable, low noise operation of components at float altitude and ambient pressure.
- demonstrate the Si(Li) cooling approach and verify thermal model.
- measure incoherent background level in a flight-like configuration.

2011 scheduled flight from Taiki, Japan
Si(Li) Tracker

- 6 commercial Semikon detectors.
- homemade detectors (test for the bGAPS fabrication).
- Energy resolution < 3 keV @ 60keV.
- operation at ambient pressure. (8mbar).
- cooling system delivers: -35°C.
Time of Flight System

- 3 planes of TOF
  1 plane = 3×3 crossed paddles
  = **18 paddles and 36 PMTs**
- 3mm scintillator (EJ-200, BC-408)
- Hamamatsu R-7600 PMT (UBA)
- timing resolution: **< 400 ps**
- charge resolution: **< 0.30 e**
- angular resolution: **8°**
GAPS anti-D Sensitivity

- Cosmic anti-D have never been detected. Could be produced by new physics.
- Primary anti-D production:
  - Supersymmetry (LSP)
  - Kaluza-Klein UED (LKP)
  - Warped ED (LZP)
  - Primordial BH’s!
- Sub-GeV region is background free – the detection of even a single, clean event would be important.

**GAPS will extend sensitivity reach by 2-3 orders of magnitude.**
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.

- **VERITAS** is fully operational 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.

- **GAPS** is a proposed balloon expt to search for signatures of dark matter in the cosmic rays. Prototype experiment is well underway.

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

*Marcel Proust (1871-1922)*
VERITAS & GAPS @ Columbia

VERITAS:
Reshmi Mukherjee
Brian Humensky

GAPS:
Chuck Hailey
Thanks!

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<tr>
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Bill Zajc
Andy Millis
and all the great folks in the main office:
Lydia A., Joey C., John C., Rasma M., Randy T., Yasmin Y.

And anyone else that I forgot!