VHE Galactic Source Highlights from VERITAS

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SACLAY Seminar, 28 July 2011
OUTLINE

- Scientific Motivations
- The atmospheric Cherenkov technique and VERITAS
- Bonus: Latest DM Results (Segue 1)
- Selection of new Galactic source results
  - Galactic Center
  - Supernova Remnants (SNRs) – Tycho
  - Pulsar Wind Nebulae (PWN) – CTA1
  - Cygnus region
  - Crab Pulsar
- Future Prospects and Summary
Scientific Motivations

Some of many motivations for Galactic VHE $\gamma$-ray sources:

PHYSICS Motivations

- Origin of Cosmic Rays
- Energy balance of Galaxy
- Physics of compact objects
- Dark matter

ASTRONOMICAL Motivations

- New observational window! (non-thermal Universe)
- High energy particle (e,p) accel.
  - shocks, stellar winds, jets, etc.

Multiwavelength Observations

- Radio
- X-rays
- Fermi LAT
Origin of Cosmic Rays

90 year old mystery!

- Enormous E range
- Mostly charged particles
- E density \( \sim 1 \, \text{eV/cm}^3 \)

Neutral messengers:

\( \gamma, \nu \)

are required to directly observe cosmic accelerators.

S. Swordy
Variety of VHE Galactic Sources

Pulsars
Pulsar Wind Nebulae

Binary systems

Supernova Remnants
NS dynamo Winds

Accretion-powered jets, Colliding winds, or …?

Star Forming Regions

Un-Identifieds
OB Assoc., WR stars
HII regions, molecular clouds

Shocks
Fermi mechanism

???
Supernova Remnants (SNRs)

- Collapse of massive star or 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 – or diffusive shock acceleration.
- In \( \sim 10^4 \) yrs, blast wave decelerates and dissipates.
- Can supply and replenish CR’s if \( \varepsilon \sim 5-10\% \).

SNR E102
Electrons or Protons?

VHE γ-rays are:

- *Not deflected* by interstellar magnetic fields.
- *Tracers* of parent particle populations – those particles accelerated by shocks, combined with possible target material.

*But both electrons and protons produce γ-rays.*

Accelerated electrons
→ TeV γ-rays
  - Up-scattering of soft photons

Accelerated protons
→ TeV γ-rays
  - Target interaction, π⁰ decay
  - π⁰ and target material

There is now good evidence for SNR acceleration of CRs, but the case is not yet ironclad.
Tracing the HE Particles

VHE $\gamma$-rays come from secondary interactions:
- $p$: $p^0$ production and decay
- $e$: Inverse Compton scattering and Bremsstrahlung

Trace beam density x target density

Need to disentangle $e$, $p$ components $\rightarrow$ MWL observations are crucial
Atmospheric Cherenkov Technique

&

VERITAS Instrument
Atmospheric Cherenkov Technique

Reconstruct IMAGE in camera of each telescope:

- Image axis $\rightarrow \gamma$-ray direction
- Intensity $\rightarrow \gamma$-ray energy
- Image shape $\rightarrow$ particle type

Stereoscopy gives greatly improved ang. resolution, E resolution, $\gamma$ / had separation, SENSITIVITY
VHE Telescopes World-Wide

Multi-messenger Astronomy ($\gamma, \nu, \text{CR}$)

Veritas

IceCube, $\nu$'s

Fermi

MAGIC

ARGO/YBJ

VERITAS

(Hess, CR's)

HESS

CANGAROO

Ice Cube

Paris (Saclay), 28 July 2011  VHE Galactic Source Highlights from VERITAS  Rene A. Ong
Collaboration of ~95 scientists
24 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)
VERITAS @ Mt Hopkins, AZ USA

Support from:
- U.S. DOE
- U.S. NSF
- Smithsonian
- STFC (U.K.)
- NSERC (Canada)
- SFI (Ireland)

U.S.
- 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.

Collaboration Mtg.
July 2011, McGill University
A VERITAS Telescope

- 12m reflector, f1.0 optics
- 350 Mirror Facets
- 500 pixel Camera
VERITAS Performance

Sensitivity
(% Crab detection, 5σ)

Using a standard Hillas moment analysis
(Improvements on the way with advanced techniques).

- Energy range: 100 GeV – 30 TeV
- Energy resolution: 15%-25%
- Angular resolution: r_{68} < 0.1°
- Pointing accuracy: < 50″

Crab Nebula γ–ray rate ~ 0.9 Hz (trigger)

VERITAS 2009+
1%: <50 h

VERITAS 2007-09
1%: <30 h
5%: 2 h
5%: 1 h
30%: 8 min
30%: 7 min

Observing (quality data)
- ~825 dark hrs/year
- ~200 partial moon hrs/year

Paris (Saclay), 28 July 2011
VHE Galactic Source Highlights from VERITAS
Rene A. Ong
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

Paris (Saclay), 28 July 2011
VHE Galactic Source Highlights from VERITAS
Rene A. Ong
VERITAS UnID Sources

Galactic Center, HESS J1857+026, MGRO J1908+06, TeV 2032+4130, VER J2019+407

http://tevcat.uchicago.edu
VERITAS Binaries

LS I +61 303
HESS J0632+303 ? (stay tuned for ICRC 2011)

http://tevcat.uchicago.edu
VERITAS SNRs and PWN

Crab Nebula, Cassiopeia A, IC 443, G54.1+0.3, G106.3+2.7, Tycho’s SNR

http://tevcat.uchicago.edu

Paris (Saclay), 28 July 2011 VHE Galactic Source Highlights from VERITAS Rene A. Ong
VERITAS New Sources (2011)

CTA 1
VER J2016+372: CTB 87
Cygnus OB1 region
(likely mult. sources)
Crab Pulsar

Other new Detections:
Galactic Center
H1426+428
BL Lacertae

http://tevcat.uchicago.edu
Latest VERITAS Results

Dark Matter
New result on Segue 1

Segue1: dSph, DM dominated

VERITAS Data set and analysis:
(M. Vivier)
- 168 runs taken between Jan 2010 and May 2011.
- Standard quality selection.
- Mean zenith angle: 19.4 deg.
- Final dataset 47.8 hrs of livetime → best sensitivity reported so far on a dSph
- No signal seen, set flux limits at $E = 300$ GeV, energy above which $E(bias) < 5\%$.
- Paper in preparation (results preliminary now).

Belokurov et al. (2007)

$\Phi_\gamma(E>E_{\text{min}}) \leq 0.5 \% \text{ Crab (95\% CL)}$

$\gamma$-ray flux limit set based on power-law spectra and DM annihilation spectra

<table>
<thead>
<tr>
<th>Spectral index $\Gamma$</th>
<th>$\Phi_\gamma^{95% \text{ CL}}(E \geq 300 \text{ GeV})$ [$10^{-13} \text{ cm}^{-2} \text{ s}^{-1}$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.8</td>
<td>7.6</td>
</tr>
<tr>
<td>2.2</td>
<td>7.7</td>
</tr>
<tr>
<td>2.6</td>
<td>8.0</td>
</tr>
<tr>
<td>3.0</td>
<td>8.2</td>
</tr>
</tbody>
</table>

TABLE II. The 95% CL ULs on the integrated $\gamma$-ray flux above $E_{\text{min}} = 300$ GeV for power-law spectra with various spectral index. For comparison, 1% of the integrated Crab Nebula flux above $E_{\text{min}} = 300$ GeV is $1.5 \times 10^{-12} \text{ cm}^{-2} \text{ s}^{-1}$. 

Power-law spectra

Preliminary
FIG. 3. 95% CL ULs on the WIMP velocity-weighted annihilation cross-section $\langle \sigma v \rangle_0$ as a function of the WIMP mass, considering different final state particles. The grey band area represents a range of generic values for the annihilation cross-section in the case of thermally produced DM. Left: hadronic channels $W^+W^-$, $b\bar{b}$ and $\tau^+\tau^-$. Right: leptonic channels $e^+e^-$ and $\mu^+\mu^-$. 

$\langle \sigma v \rangle_{\text{min}} \leq 1-8 \times 10^{-24} \text{ cm}^3 \text{ s}^{-1}$

Limits are factor of 4-5x better than our previous dSph results and best on dSph reported so far.
New VERITAS Results on Galactic VHE Sources
Galactic Center

Complex region:
- Sgr A*, ~3x10^6 solar mass BH.
- Possible SNRs or PWN
  - increased level of CR density.
- Transients seen in X-rays, GeV γ-rays.
- Dark matter?

GeV / TeV Observations:
- EGRET: strong source 3EG 1746-2851.
- CANGAROO-II (2001/2): 10% Crab, steep spect.
- Fermi-LAT: Numerous sources in region.
LZA Observations

Large Zenith Angle (LZA) method:
- Large effective area at high energies.
- Increased $E_{th}$ and poorer angular recon.

Displacement method:
- New parameter into 6-dim lookup table.
- Combine with standard geometric method.
- Test using LZA observations of Crab.

Significantly improved angular resolution and sensitivity

M. Beilicke, G. Senturk
VERITAS GC Observations

2010-11 Observations:
- 24.7 hrs, zenith ~65°, E > 2 TeV
- 14σ detection
- No evidence for variability

Sky map:
- Excess at GC, fit position:
  \( l = -0.06 \pm 0.02; \ b = -0.06 \pm 0.01 \)
- Consistent with H.E.S.S. (overlay)

5σ detection possible in ~3h
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VERITAS GC Energy Spectrum

Spectrum (preliminary):

- Compatible with Whipple, H.E.S.S. and MAGIC.
- Conservative flux systematic ~40% (from Crab LZA).

Comparison to some models:

- Hadronic accelerator models near BH - (Chernyakova et al. 2011) and (Ballantyne et al. 2011).
- Plerion wind model of (Atoyan et al 2004).

Future:
Improved >10 TeV data (spectrum & variability) to constrain cut-off.
VERITAS Supernova Remnants

Cas A
Age = 300y
D = 3.4 kpc

~3% Crab

Tycho
Age = 440y
D = 2-5 kpc

~1% Crab

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

Tycho’s SNR:

- Historical Type 1a SN of 1572.
- X-ray morphology argued for hadronic acceleration (Warren et al. 2005).
- VERITAS discovery in 2010 with 68 hrs.
- Weak source (0.9% Crab) with hard power-law spectrum $\Gamma = 1.95 \pm 0.51 \pm 0.30$.
- Consistent with leptonic or hadronic models.
Fermi-LAT & VERITAS:

- New Fermi-LAT detection ($5\sigma$).
- Hard photon index of $2.3 \pm 0.1$ favors hadronic origin.
- 6-8% of $E_{sn}$ transferred to CR acceleration ($D \sim 2.8$ kpc).

Good evidence for hadron accelerator; similar for Cas A
CTA 1: First Blind-Search Fermi Pulsar

CTA 1:
- Composite SNR with an X-ray filled radio shell ~1.8° diameter.
- Age ~ 13ky, D~ 1.4 ± 0.3 kpc.
- No known pulsar (before Fermi).

Fermi-LAT Observations (2008):
- Pulsar discovered in blind search in first four months of data – coincident with X-ray source, presumed PWN.
- Period = 316.9ms, \( E_{\text{cutoff}} \approx 5 \text{ GeV} \); characteristic pulsar age ~ SNR age.
- X-ray pulsar subsequently detected with Chandra (P. Caraveo et al. 2010).

A. Abdo et al., Science 322, 1218 (2008)
VERITAS Observations:
- 26 hrs, Oct 2010-Jan 2011 at 0.7° wobble.
- Search region: circle of r=0.4°, tiled in 0.04° square sections; pt-source & ext cuts.
- Trials factor ~ 1300.

Detection:
- Significance ~6.3σ post-trials.
- F (> 1 TeV) ~ 4% Crab Nebula.
- Clearly extended source.

S. McArthur, R. Mukherjee

VERITAS preliminary
CTA 1: VERITAS Detection

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**MWL Picture:**
- VERITAS emission surrounds the Fermi-LAT pulsar.
- Properties of CTA 1 in middle range of known TeV/X-ray PWN.

Good evidence that CTA 1 is a PWN (new indications from Fermi-LAT too)

Color: VERITAS excess map with green contours from 3-7σ.
Black: Radio 1420 MHz (T. Landecker).
Red: Fermi-LAT error circle.
VERITAS Cygnus Sky Survey

VHE Sky Surveys:
- **HEGRA (97-02)**: North, ~25% Crab.
- **HESS (03-04)**: South, ~3% Crab and extended (05-08).
- **Milagro (01-07)**: North, ~35% Crab at E > 10 TeV.

VERITAS Sky Survey (07-09):
- N. Hemisphere – Cygnus arm.
- 115h + 55h follow-up; done before improvements to sensitivity.
- ~3% Crab (99%) for E > 200 GeV.
Survey exposure map
- Survey done by pointings spaced by 0.8° in l and 1.2° in b.
- Overall scope limited by summer and weather conditions.

Left side region (2010)

TeV J2032+4130
- First UnID TeV source

VER J2019+407
- New source near γ-Cygni.
- SNR interaction with HI shell?

Now, discuss some results from region B.
Cygnus OB1 ("Cisne", "Dragonfly")

MGRO J2019+37

- Brightest new source in Milagro survey, ~80% Crab, E>15 TeV (A. Abdo et al. 2007). (But not seen by ARGO/YBJ… ?).
- Coincident with two EGRET sources – one proposed as blazar (Mukherjee et al., 2000) and other proposed as PSR J2021+3651 (Roberts et al. 2002) – both sources confirmed by Fermi-LAT.
- Large effort to look for counterparts in radio (Parades 2009) and X-ray (Zabalza & Parades 2010).
- Origin of 10 TeV emission not clear – PWN? Shocks from WR stars in OB1 complex (Bednarek 2009)?
VERITAS Observations of Cygnus OB1

Observations and Analysis:
- 75h, May-Dec 2010.
- 0.7° wobble around PSR J2021+3651.
- Pt-source and extended search (0.25°).
- Hard cuts, $E_{th} \sim 600$ GeV.

Results:
- Point source and extended source both detected above 6σ, post-trials.
- The extended source is a complex region, most likely made up of multiple sources.

E. Aliu et al., 3rd Fermi Symposium (2011)
VER J2016+372 and Cisne

VER J2016+372:
- Consistent with CTB 87 (PWN candidate).
- At edge of B 2013+379 (blazar).
- 1FGL J2015.7+3708 most consistent with blazar (variability seen).
- VERITAS source is likely a new TeV PWN, not seen at GeV energies.

Cisne:
- VERITAS data consistent with MGRO J2019+37, but reveals more detail.
- Most likely multiple (possibly extended) sources.
- Need more VHE and lower energy data; Fermi-LAT analysis to be presented at ICRC 2011 (Beijing).
Crab Nebula and Pulsar

- Remnant from historical SN in 1054.
- One of the most energetic pulsars and brightest $\gamma$–ray pulsars.
- Nebula is the brightest, steady VHE source.

$\gamma$-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 $E_{\text{th}}$.
- 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.
- Curvature radiation – most-favored $\gamma$-ray production mechanism.
- Emission come from outer regions $>6$ stellar radii. Outer-gap or slot-gap models favored.
VERITAS Observations:

- Total of 107h of data (2007-09: 45h, 2010: 62 h), taken with 4 telescopes.
- Wobble with 0.5° offset.
- Zenith angle < 25°.
- Event times from four independent GPS receivers (1 μs accuracy).

Analysis (N. Otte, A. McCann, M. Schroedter):

- Standard trigger, standard analysis tools (two independent packages).
- Hillas image analysis with stereo reconstruction.
- Analysis selection set a priori for weak (few % Crab Nebula) source with soft spectrum, $\Gamma = 4$.
- Event time barycentering with two custom codes and tempo2.
- Phase folding of data using Jodrell Bank empherides.
VERITAS Pulsed Signal

Statistical significance of pulsed signal:
H-Test value of 50, i.e. 6.0σ.
Pulse positions **aligned with peak positions in radio**. The shift with respect to Fermi-LAT data is an analysis effect.

- **P1**
  - Position: $-0.0023 \pm 0.0020$
  - Width: $0.0132 \pm 0.0035$ FWHM

- **P2**
  - Position: $0.3975 \pm 0.0020$
  - Width: $0.0268 \pm 0.0052$ FWHM

Pulses above 120 GeV **2-3 times narrower than in Fermi-LAT data** → possible interpretation: the acceleration zone tapers.
VERITAS VHE Spectrum:

- Combine P1 and P2 regions – good approx. of phase-averaged spectrum.
- Highest energy point at 280 GeV.
- Crab Pulsar ~ 1% Nebula flux at 150 GeV.
- **Power-law form**!
  \[ \frac{dN}{dE} = A(E/150 \text{ GeV})^\alpha \]  
  for \( \alpha = -3.8 \pm 0.5^{\text{stat}} \pm 0.2^{\text{syst}} \)
• First detection of a pulsar above 100 GeV.
• VERITAS detection @ 280 GeV $\rightarrow$ emission region $\geq$ 10 stellar radii.
• Absence of exponential cutoff $\rightarrow$ rules out curv. radiation as dominant mech.
• Narrowing of pulses $\rightarrow$ tapered acceleration region?
• What other pulsars are out there at E $>$ 100 GeV?
Future Prospects: VERITAS Upgrade

VERITAS in 2011:

- Operating smoothly in excellent sensitivity and science output.
- With excitement of field (and power of Fermi), we want to improve sensitivity – especially at ~100 GeV.

VERITAS UPGRADE (2009-2012):

1. Improved optical point spread function ← completed
2. Relocating telescope T1 ← completed
3. Upgrading cameras with high efficiency PMTs ← ongoing
4. New trigger system ← ongoing
5. An additional telescope T5 ← possible in the future
VERITAS Trigger & PMT Upgrade

Trigger upgrade (2009-2011):
- Camera trigger processing done by special (L1.5) FPGA-trigger cards.
- L2 processor combines L1.5 signals.
- Deployed June-Sept 2011.

Camera upgrade (2010-2012):
- Replace all PMTs with HQE ones (Hamamatsu R9800 SBA); new mount tube and pre-amp.
- Improve sensitivity and lower E threshold (120 GeV → 80 GeV).
- Installed Summer 2012.
Summary

Lots of new results from VERITAS:

- **Dark Matter**: New result by VERITAS from *Segue 1*.
- Galactic Center: competitive observations possible using LZA technique.
- SNRs: we detect young shell-type SNRs directly and older ones through interaction with material. *Tycho* is a relatively clean system that supports hadronic acceleration picture.
- **CTA 1**: VHE discovery by VERITAS; indicates a likely PWN.
- Cygnus Region: new sources: **VER J2019+407** (γ-cygni, OB2) and – **VER J2016+372** (CTB 87, OB1) neither seen (yet) by Fermi-LAT. *MGRO J2019* is complex object likely containing multiple sources.
- **Crab Pulsar**: detected for first time above 100 GeV. Pulse profile is different than at lower energies – new understanding of pulsars needed!
- VERITAS is operating well and will further improve with upgrade (2012).