VERITAS – Status and Results

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Physics Department and McDonnell Center for the Space Sciences

Science with the New Generation of
High Energy Gamma-Ray Experiments
6\textsuperscript{th} workshop, October 8-10, Padova, Italy

- Status of VERITAS
- Galactic Observations
- Extragalactic Observations
- Summary and Conclusions
STATUS OF VERITAS
The VERITAS Collaboration

Fred Lawrence Whipple Observatory

- Smithsonian Astrophysical Observatory
- Purdue University
- Iowa State University
- Washington University in St. Louis
- University of Chicago
- University of Utah
- University of California, Los Angeles
- McGill University, Montreal
- University College Dublin
- University of Leeds
- Adler Planetarium
- Argonne National Laboratory
- Barnard College
- dePauw University
- Bartol Research Institute/University of Delaware
- Grinnell College
- University of California, Santa Cruz
- University of Iowa
- University of Massachusetts
- Cork Institute of Technology
- Galway Mayo Institute of Technology
- National University of Ireland Galway
- ~25 Associate Members
A VERITAS Cherenkov Telescope

PMT camera

12m diameter (area: 110 m²)

3.5° FOV
499 pixels (Photonis XP2970)
The VERITAS Cherenkov Telescope Array

Fred Lawrence Whipple Observatory

T2 (Spring 06)  T1 (Jan 05)  T4 (Spring 07)  T3 (Fall 06)

- Very Energetic Radiation Imaging Telescope Array System
- Array fully operational since Spring 2007
- Energy range: 100 GeV up to ~30 TeV (resolution: <20%)
- Sensitivity: 10% (1%) Crab in <1h (<50h)
The VERITAS Cherenkov Telescope Array++

Whipple 10m (AGN monitoring)

T1
Jan 2005

T2
Spring 2006
85m

T3
Fall 2006
82m

T4
Spring 2007

7km
103m
35m

AGN monitoring
Array: Angular Resolution & Sensitivity

- Tight cuts (weak source sensitivity):
  \( \text{size} > 400 \text{dc} \) (~75 p.e.), \( \Delta \theta^2 < 0.015 \text{deg}^2 \), \( N_{\text{mult}} = 4 \)

5 Detection Sensitivity

- 1% Crab in 47 hours
- 5% Crab in 2.5 hours

Simulated Gamma-Rays

Crab Nebula

68% Containment within 0.1°
Array: Off-axis Sensitivity

- Measured on Crab Nebula
- Physical camera radius: 1.75 deg

Capability: source detections beyond physical camera extension
Observation Planning & Key Science Projects

- **Key Science Projects**
  - Blazars
  - Dark Matter
  - Galactic Plane Survey
  - Supernova Remnants

- Open time for SWG proposals, administered by the VERTIAS TAC

- Spokesperson’s Discretionary Time for Engineering and ToOs
The 2007/2008 Observing Season

Oct07–Jun08 season: Good weather, 4tels: ~700h + moon data (~100h)

Discoveries: 1ES0806+524 (Atel 1415), W Com (Atel 1422) & 3C66A (Atel 1753)

Flaring sources: Mrk421 (Atel #1506), W Comae (Atel #1565) & M 87

Source observations (partially including MWL coverage): Crab, Cas A, IC 443, LSI+61, HESSJ1908, Mrk421, Mrk501, 1ES2344, 1ES1959, 1ES0806, 1ES1218, WComae, M87, and many more...

TevCat: http://tevcat.uchicago.edu
GALACTIC OBSERVATIONS
Cas A

- Young SNR (330 years), 5 arcmin
- Discovered by HEGRA (232h, 5σ) confirmed by MAGIC (47h, 5.3σ)
- **VERITAS** observations:
  => Oct/Nov 2007 (20h, 9.8σ)
  => Flux level: ~3% of the Crab
  => no indication for extension (ongoing)
  => Energy spectrum: work in progress
- Open question: hadronic or leptonic accelerator

VERITAS data will allow most accurate energy spectrum

Contact: A.Konopelko, B.Humensky, T.Ergin
IC 443

- SNR shell, mol. cloud interaction & PWN
- Discovered at VHE in 2007 by:
  => MAGIC (29h, 5.7σ) [Albert et al. 2007]
  => VERITAS (16h, 6σ)
- Total VERITAS observations (31h, 8.2σ):
  -> Feb/Mar 2007 (3 telescopes)
  -> Oct/Nov 2007 (4 telescopes)
- Position compatible with MAGIC,
  Extension: $\sigma = (0.17 \pm 0.02_{\text{stat}} \pm 0.04_{\text{syst}})$ deg
- Bright star: different BG models, MC
- VHE emission:
  => CR interaction with molecular cloud?
  => associated with PWN in the north?

Energy spectrum: Work ongoing

Contact: B.Humensky, S.Bugaev
High-mass X-ray binary
Variable VHE $\gamma$-ray source (seen by MAGIC/VERITAS)
Emission mechanism unknown: Microquasar or interacting PWN? (+strong propagation/absorption effects)

Orbital period: 26.5d

Contact: G. Maier
VERITAS observations of LSI +61 303 (2 years)

2006-2007
45 h of 2/3-telescope data

2007-2008
12 h of 4-telescope data
(analysis of data taken in moonlight conditions still ongoing)

Rich set of X-ray and γ-ray data:
Correlation between γ-ray emission and X-ray emission?

Contact: G.Maier
GeV/TeV (anti)correlation in VHE binaries

Photon fields (dense and anisotropic):
=> phase-dependent VHE emission (pair productions)

Inverse Compton production of HE γ-rays
attenuation by pair production

Different flux modulation vs. orbital phase expected for GeV and TeV energies
VERITAS observations of Pulsar Wind Nebula

Contact: E.Aliu

PWNe are largest class of galactic γ-ray sources
Evidence for acceleration of electrons up to 100 TeV
VERITAS observed selection of pulsars with large energy loss:
$\frac{dE}{dt}/d^2 > 10^{35} \text{ ergs/s/kpc}^2$

<table>
<thead>
<tr>
<th>Object</th>
<th>$\log_{10}\frac{dE}{dt}/d^2$ [erg/s/kpc$^2$]</th>
<th>T [hrs]</th>
<th>$&lt;Z&gt;$ [deg]</th>
<th>Significance [$\sigma$]</th>
<th>F($E_{\text{th}}$) [% Crab]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crab Nebula</td>
<td>38.1</td>
<td>11</td>
<td>15</td>
<td>100</td>
<td>100</td>
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<tr>
<td>PSRJ0205+6449</td>
<td>36.4</td>
<td>12.8</td>
<td>35.2</td>
<td>1.1 (1.5)</td>
<td>&lt;2.3 (4.1)</td>
</tr>
<tr>
<td>PSRJ0631+1036</td>
<td>33.6</td>
<td>13.0</td>
<td>24.5</td>
<td>0.3 (0.4)</td>
<td>&lt;1.3 (2.1)</td>
</tr>
<tr>
<td>PSRJ0633+1746</td>
<td>36.1</td>
<td>13.3</td>
<td>17.6</td>
<td>-0.1 (0.6)</td>
<td>&lt;1.0 (2.2)</td>
</tr>
<tr>
<td>PSRB0656+14</td>
<td>35.6</td>
<td>9.4</td>
<td>22.4</td>
<td>-1.8 (-2.6)</td>
<td>&lt;0.2 (0.7)</td>
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<tr>
<td>PSRJ1740+1000</td>
<td>35.1</td>
<td>10.5</td>
<td>24.6</td>
<td>0.2 (0.0)</td>
<td>&lt;1.0 (1.4)</td>
</tr>
</tbody>
</table>

99% upper limits, flux above 300 GeV
VERITAS observations of MGRO J1908+06

- Unidentified Milagro source (80% Crab @ 20 TeV)
- Detected at VHE energies by H.E.S.S.
- No counterpart identified, candidates:
  => SNR G40.5-0.5
  => EGRET 3EG J1903+063
- **VERITAS** observations (22h):
  => Detection at ~5σ level
  => Position: compatible with position reported by H.E.S.S.
  => Extension: ~0.2deg

Contact: J.E.Ward, A.Weinstein, A.Konopelko, T.Ergin, M.Beilicke
The Auger Cosmic Ray / AGN correlation

- Auger: Anisotropy in CR arrival directions (E>50EeV), correlated with AGN (Veron/Cetty, z<0.018) [Science, 318, 939 (2007)]
- Encouraged VERITAS observations:
  => Pair A (3.3h) & Pair B (10.1h)
- No significant excess found

Contact: J. Holder
The AGILE transient

- AGILE reported strong transient
  => E>100MeV
  => comp. with 3EG J2020+4017
  => variable emission (April 2008)
  => ATel#1492
  => AGILE J2021+4024

- VERITAS observations: ~7h

- UL (99%): ~2% Crab (non-simultaneous)

Contact: G.Maier
The VERITAS sky survey

ongoing...

Contact: R.Ong
EXTRAGALACTIC OBSERVATIONS
Active Galactic Nuclei (AGN) and Blazars

- AGN: Black hole and accretion disk power relativistic plasma jet
- SSC model:

Open question: TeV emission: hadronic vs. leptonic models
### The Extragalactic VHE sky: AGN and Blazars

<table>
<thead>
<tr>
<th>Name</th>
<th>redshift</th>
<th>reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Markarian 421</td>
<td>0.030</td>
<td>Punch et al., Nature, 358, 477 (1992)</td>
</tr>
<tr>
<td>Markarian 180</td>
<td>0.045</td>
<td>Albert et al., astro-ph/0606630 (2006)</td>
</tr>
<tr>
<td>1ES 1959+650</td>
<td>0.047</td>
<td>Nishiyama et al., 29th ICRC, 3, 370 (1999)</td>
</tr>
<tr>
<td>PKS 548-322</td>
<td>0.067</td>
<td>Proc. Of ICRC 2007</td>
</tr>
<tr>
<td>BL Lacertae</td>
<td>0.069</td>
<td>Albert et al., astro-ph/0703084 (2007)</td>
</tr>
<tr>
<td>W Comae</td>
<td>0.102</td>
<td>Swordy et al 2008, ATeI #1422</td>
</tr>
<tr>
<td>1ES 0806+524</td>
<td>0.138</td>
<td>Swordy et al 2008, ATeI #1415</td>
</tr>
<tr>
<td>1ES 0229+200</td>
<td>0.139</td>
<td>Proc. Of ICRC 2007</td>
</tr>
<tr>
<td>1ES 0347-121</td>
<td>0.188</td>
<td>Proc. Of ICRC 2007</td>
</tr>
<tr>
<td>S50716+714</td>
<td>??</td>
<td>Teshima et al 2008, ATeI #1500</td>
</tr>
<tr>
<td>3C 66A</td>
<td>&gt;0.096</td>
<td>Swordy et al 2008, ATeI #1753</td>
</tr>
</tbody>
</table>

Except for M87, all extragalactic TeV γ-ray sources are blazars
Discovery of 1ES0806+524

- HBL (redshift z=0.138)
- Predicted VHE emission
  [Costamante 2002]
- VERITAS detection:
  40h, $5.8\sigma$, ATel#1415
- Photon flux:
  $(1.1 \pm 0.2_{\text{stat}})\%$ of Crab
  [good weak source sensitivity]

First 'VERITAS discovery': 1ES0806+524

Contact: P.Cogan
Detection of the IBL W Comae

- Intermediate-frequency-peaked BL Lac (IBL, z=0.102)
- VERITAS obs. in 2008 (39.5h)
- Detected with 4.9 std.dev.
- Strong flare (March): ATel#1422
- First time: 2 extragalactic VHE sources in one FoV.

Contact: M. Beilicke
Detection of the IBL W Comae

- Steep energy spectrum, modeling:
  => SSC (unusual low B-field: 0.007G)
  => SSC+EC (more realistic parameters)

- Second VHE flare (June, Atel#1565)
  => triggered Agile (ATel#1582)

Discovery of 3C 66A

First evidence: Crimean IACT  
[Neshpor et al (1998)]

VERITAS detection (2007/08):  
>8σ, ATel#1753

Spectrum: soft  
Integral flux: ~10% Crab

Redshift uncertain:  
o) Weak line (Mg II?) => z = 0.444  
[Miller, French & Hawley (1978)]  
o) Weak Ly-alpha line  
[Lanzetta et al. (1993), ApJS, 84, 109]  
o) Limit (photometric z): z > 0.096  
[Finke et al. (2007), A&A, 447, 513]

=> GASP: Optical/near-IR brightening (Atel#1755)

=> Fermi detection (ATel#1759)

Contact: L.Reyes, J.Perkins

Third 'VERITAS discovery': 3C 66A
VERITAS observations of 1ES1218+304

- HBL (redshift z=0.182)
- Discovered by MAGIC [Albert et al. 2006]
- VERITAS observations: 17h, 10.4σ
  => Photon flux: ~6% Crab (no variability)
  => Photon index: $\Gamma = 3.08 \pm 0.34_{\text{stat}} \pm 0.2_{\text{syst}}$

- De-absorbed energy spectrum:
  => EBL limit (gal. count): $\Gamma_{\text{int}} < 2.32 \pm 0.37$
  => +blazar constraints: $\Gamma_{\text{int}} < 1.86 \pm 0.37$
  => HE peak beyond 2 TeV

Extending the 1ES1218 spectrum to 10 TeV: constrain EBL

Contact: P.Fortin, F.Krennich
The Giant Elliptical Radiogalaxy M 87

- Distance: 
  \(~16 \text{ Mpc}\) 
  \((z=0.00436)\)

- Central BH: 
  \(M_{BH} \sim 3 \cdot 10^9 \text{ M}_{\odot}\)

- Jet angle: \(~30^\circ\) 
  \(\Rightarrow\) not a blazar!

- Structures of the jet resolved at radio, optical and X-ray energies

- Predictions of TeV \(\gamma\)-ray emission and charged \(10^{20}\) eV particles (UHECR)
M87: 10 Years of VHE Observations

History:

HEGRA (>4σ excess):
[Aharonian et al. 2003]

Whipple (upper limit):
[Lebohec et al. 2003]

H.E.S.S. (11σ confirmation, short-term variability):
[Aharonian et al. 2006]

VERITAS (detection):
[Acciari et al. 2008]

MAGIC (confirmation of short-term variability):
[Albert et al. 2008]

Thanks to D.Harris!
(Chandra light curves)

Contact: M.Beilicke
A joint M87 Observation Campaign in 2008

- Coordinated campaign: H.E.S.S./MAGIC/VERITAS
- More than 120h (>50 nights)
- **Outburst** in February 2008 (triggered by MAGIC, occurred during X-ray low-state of HST-1)
- 5 Chandra pointings in 2008

Key question: origin/location of the TeV emission

Contact: M.Hui, M.Beilicke, H.E.S.S. And MAGIC
Mrk421: 2007/08 MWL Campaign

**MWL data:**
- **Radio:** Metsahovi, UMRAO (tbd)
- **Optical:** BRT/NMS, UVOT, RCT/Bell/CRAO, WIYN, Turola/KVA (tbd)
- **X-ray:** RXTE (ASM&PCA), Swift (BAT&XRT), Suzaku (tbd)

**VERITAS data:**
- 42h of data in 2008
- Night-by-night light curve (assuming dN/dE ~ E^{-2.5})
- Whipple results will follow

Underway: Spectral variability, MWL flux correlations

Contact: J.Grube, L.Reyes, M.Daniel, M.Beilicke
Mrk421: TeV & X-ray Correlations

Correlation studies (preliminary):
- Flux vs. index (X-ray & TeV)
- X-ray/TeV flux

Underway: Spectral variability, MWL flux correlations

Contact: L. Reyes, M. Daniel, M. Beilicke
Mrk421: The big Flare (May 2008)

- Big flare recorded begin of May '08
- Flux level up to 10 Crab
  [Swordy et al 2008, ATel#1506]
- $5\sigma$-detection in ~15s(!)

Contact: L.Reyes, M.Daniel, M.Beilicke

More studies underway...
1ES 2344+514 (z=0.044): TeV/X-ray Light Curve

X-ray data:
- 53 RXTE/PCA pointings
  - STD QL selection
  - RXTE faint BG model
  - Fit data with power law
- Swift data
  - power-law fit (0.6-10keV)

VERITAS data:
- 23h of data in 2007/2008
- Night-by-night light curve

4\textsuperscript{th} VHE blazar with good MWL coverage

Contact: J.Grube, L.Reyes, D.Horan, M.Wood, M.Beilicke
Observation of Dwarf Galaxies (DM)

Draco
20h, φ < 1.1% Crab

Ursa Minor
20h, φ < 0.8% Crab

Willman I
15h, φ < 1.1% Crab

Future Constraint by LHC

Whipple 10m
Ursa Minor constraint

VERITAS
Willman I constraints derived from Strigari et al. 2007

Minimal Supersymmetric extensions to Standard Model (MSSM) allowed by WMAP

Contact: M.Hui
Summary and Conclusion

Total observations in 2007/2008 season: 700h (+100h moon)

Galactic objects
- **Detected**: Crab, Cas A, MGRO J1908+06
- **LSI+61**: flux modulation with orbital phase, MWL observations
- **IC443**: detected in 2007/2008 (~8σ), extended

Extragalactic observations
- **Discoveries**: 1ES0806, W Comae (IBL) and 3C 66A
- **M87**: detected in 2007/2008 (joint campaign with H.E.S.S. And MAGIC)
- **Mrk421**: Extensive VERITAS/RXTE/Swift campaign in 2008
- **1ES2344**: VERITAS/RXTE/Swift MWL, flaring up to 0.4 Crab
- **More AGN/blazars**: observed/analyzed (not addressed here)

Thanks go to the RXTE, SWIFT and AAVSO teams.