Outline

• VERITAS Overview
• Galactic Science
• Extragalactic Science
• Particle Astrophysics
• Future Prospects
• Summary
Monitoring Capability

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VERITAS Instruments

Davies-Cotton f/1.0 Optics. Total area = 110m$^2$

- FOV ~ 3.5°
- Pix. ~ 0.15°
- 500 Pixels
- 500 Msp/s
VERITAS Performance

- Energy range: 100 GeV - 30 TeV
- Energy resolution: 15% - 20%
- Spectral reconstruction: E > 150 GeV
- Angular resolution (per event): \( r_{68} = 0.1^\circ \)
- Crab rate 37 min\(^{-1}\) (trigger level)
- 1% Crab detection in less than 50h,
- 5% crab in \( \sim 2.5 \) hours

Design Sensitivity already met!

20% better Sensitivity Fall 2009 -
VERITAS Science Program

Observations:
~ 800 hrs / year
+ ~ 200 hrs / year moonlight

Discretionary (10%)
ToO’s
GRB’s (priority)
etc.

Key Science Projects (50%)
Sky Survey
(Cygnus region)
BLAZARS
SNRs/PWN
Dark Matter

Science Groups:
Astroparticle
Physics
Blazars
Dark Matter
Extragal. Sources
Galactic Compact
Galactic Diffuse
GRB’s
PWN & SNR’s
Unidentifieds

Bulk Program (40%)
VERITAS Detections

Blazar Science

- 4 source discoveries
- 11 detections - detailed studies - multiwavelength campaigns (Blazars, radio galaxy)

Galactic Science

- 1 discovery (SNR)
- 4 detections - detailed studies - multiwavelength campaigns (X-ray Binary, Unid., SNR)

Survey of Cygnus region
Galactic Sources
Supernova Remnants: IC443

- middle aged, 3-30 kyr
- distance: 1.5 kpc
- shell structure optical/radio
- diameter: 0.75°
- Molecular Cloud (CO)
- PWN CXOU J061705.3+222127
- interesting for TeV studies

- VERITAS/MAGIC Co-discovery
  -> VERITAS: 6.0 $\sigma$ (7.1 $\sigma$ pre-trial) in 15.9 h
  -> MAGIC: 5.7 $\sigma$ in 29 h

- VERITAS deeper observations: 37.9 h
  -> 8.3 $\sigma$
Supernova Remnants: IC443

TeV emission:
- **extended**: $0.16^\circ \pm 0.03^\circ$
- coincides with MC (d densest part)
- associated with PWN (10’ offset)
- Maser emission
- could arise from neutral pion interaction in MC or from relic electrons produced by pulsar and still residing in MC
- critical are GeV/TeV studies

Energy spectrum:
\[ \frac{dN}{dE} = (8.38 \pm 2.10) \times 10^{-13} E^{-2.99 \pm 0.38} \]
photons TeV$^{-1}$ cm$^{-2}$ s$^{-1}$

Supernova Remnants: Cas A

- Young (330 yr), Shell-type
- Distance ~ 3.4 kpc
- massive star progenitor
- 0.08 deg. diameter ~ TeV PSF
- Discovered in TeV by HEGRA
- (232 hrs, 5\( \sigma \)), confirmed by MAGIC (47 hrs, 5.3\( \sigma \))
- Flux 3.3% Crab
- \( \Gamma = 2.3 \pm 0.2_{\text{stat}} \pm 0.2_{\text{sys}} \)

Deep Chandra image of Cas A (7.3’ by 6.4’)

[Image of Cas A with a deep Chandra image]
Supernova Remnants: Cas A

- 8.3 $\sigma$ in 22 hours
- Flux 3% Crab
- consistent with point source
- upper limit on source extension 2'$
- $\Gamma = 2.61 \pm 0.24_{\text{stat}} \pm 0.20_{\text{sys}}$

Acciari et al., in preparation (2009)
Northern Pulsar Wind Nebulae

- Strong candidates for TeV emission (8 PWN in southern hemishere by HESS)
- selection of pulsars with high energy loss rate and per distance$^2$
- Most sensitive survey of PWN at high gal. longitudes

- nearby pulsar (e+ excess in C.R. spectrum? arXiv:0810.2784v2)
- Milagro excess at ~ 35 TeV (arXiv:0904.1018)

<table>
<thead>
<tr>
<th>Source</th>
<th>log10 (E/d^2) [erg/s/kpc^2]</th>
<th>time [hrs]</th>
<th>σ</th>
<th>F(E&gt;300 GeV) [% Crab]</th>
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<tr>
<td>Crab Nebula</td>
<td>38.1</td>
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<td>0.2</td>
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</table>
X-ray Binary LS I +61 303

- High-mass X-ray binary at ~2 kpc: massive Be star + compact companion (neutron star / BH)
- Orbital period 26.5 days with $\epsilon \sim 0.7$
- Radio / X-ray emissions correlated with orbital period

- Emission mechanism unknown: Microquasar or interacting PWN? (+strong propagation/absorption effects)
- TeV emission discovered by MAGIC in 2006, confirmed by VERITAS
- 10 - 20% Crab at apastron


LS I +61 303: Fermi/VERITAS

- No detection during Fermi high state emission (periastron)
- spectra line up well (?), but fluxes are anti-correlated

VERITAS November 2008

F(E>500 GeV) < 1.26x10^{-12} cm^{-2}s^{-1}
(2.1% Crab, 99% CL)

VERITAS: dN/dE=2.89x10^{-12}E^{-2.40}

Fermi: dN/dE=2.68x10^{-12}E^{-2.41}

- Point-like Unid. (1 of 2)
- Detected by HESS in 2004
- VERITAS Obs. Dec 2006, 2008, Jan 2009: upper limit ~ 1% Crab
- Rejection of constant flux hypothesis at prob. 0.007% (4 $\sigma$)
- Interpretation: Binary system?
- Coincident with Be star MWC 148
- No companion yet detected; no information on period
- Variable X-ray emission (Hinton 2009)

- AGILE transient $E > 100$ MeV
- Consistent with 3EG J2020+4017
- Astronomer's telegrams (#1492, 1547, 1585) issued on Apr 28, May 27, and Jun 23 2008 by AGILE
- VERITAS observation 7 hours between Apr 29 – May 6 2008
- Preliminary upper limit
  $F(E > 300$ GeV$) \sim 2\%$ Crab (99% CL)
Extragalactic Sources
Discovery: 1ES 0806+524

- one of “best candidate” TeV BL Lacs (Costamante & Ghisellini 2002)
- HBL
- $z = 0.138$
- $5.8 \sigma$ in ~ 40 hours
- flux $\sim 0.01$ Crab
- weakest VERITAS blazar
- spectrum appears soft:
  $N/dE \sim E^{-3.6\pm1.0}$

Discovery: W Comae

- discovered in radio 1971, in X-ray 1980
- IBL (falls between LBL-HBL)
- seen by EGRET: 0.1 - 10 (27) GeV
- $z = 0.102$
- $4.9 \sigma$ in ~ 40 hours
- outburst March 08 (> 8 $\sigma$ detection)
- Quasi-simultaneous X-ray data (Swift)

$\sigma_t = 1.29 \pm 0.28$ days
- one zone SSC model yields a weak B-field
- EC yields $B \sim 0.3\,\text{G}$
- GeV - TeV coverage is critical

\[ \frac{dN}{dE} \propto E^{-3.81 \pm 0.35_{\text{stat}}} \]

Quasi-simultaneous data March 14/15 2008 from AAVSO, UVOT, XRT, VERITAS
**Discovery**: 3C66A

- EGRET detection, Fermi (ATEL #1759)
- Crimean* group 5.1 $\sigma$ in 1996 - 98
- 2nd IBL in TeV: VERITAS (ATEL#1753)
- $z=0.44$ highly uncertain
- $z > 0.096$ (Finke et al 2008)

- TeV Emission is consistent with 3C66A
- Upper limit on 3C66B

- MAGIC detection of 3C66B in '07
  5.4 $\sigma$ in 54 h, 2.7% Crab
- VERITAS detection of 3C66A in ‘07-08
  21$\sigma$, $\sim$1800 $\gamma$; $E_{th} \sim 120$ GeV; in 33 h
- spectral index is $\Gamma = 4.1 \pm 0.4_{stat} \pm 0.6_{stat}$
- if $z=0.44$ then $\Gamma_{intr} = 1.1 \pm 0.4$

- HBL, z ~ 0.125
- Discovered by VERITAS as part of
- “blazar filler” program
- ATel #1941, 2/24/2009
- 22 hrs livetime, 6.3 $\sigma$, 140 $\gamma$-rays
- Multiwavelength data, analysis in progress

Acciari et al., in preparation (2009)
Mrk 421

- Observed: Jan - June 2008,
- ~40 h, ~280σ, >30,000 γ
- Whipple 10-m Alert! ATel #1506;
- Swift, RXTE, optical/radio
- Flux: 0.3 - 10 Crab
- VERITAS light-curves w/ minute-scale bins
- Peak detection: 5σ in ~15s
- VHE & X-ray fluxes are highly correlated
- VHE & X-ray spectra harden w/ high flux
- VERITAS 2006-08 data: Paper in ~months
- June ’08: VERITAS, MAGIC, AGILE + X-ray/Optical
Distant Blazars: 1ES1218+30.4

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Courtesy of M. Beilicke

Courtesy of P. Fortin

\[ \frac{dN}{dE} \propto E^{-3.09 \pm 0.34_{\text{stat}}} \]

\[ z = 0.182 \]
Distant Blazars: \(1\text{ES1218+30.4}\)

\[\Gamma = 1.30 \pm 0.38\]

\[\frac{dN}{dE} \propto E^{-3.09 \pm 0.34_{\text{stat}}}\]


Courtesy of P. Fortin
M87

- Non-blazar:
  - Jet ~ 30º, D~16 Mpc
  - SMBH ~3x10⁹ M_{sun}
- jet structure: radio-optical-X-ray
- variable in X-rays
- TeV “image” is not resolved
- VERITAS low-state detection in 2007
- Point-like (>250 GeV) emitter at core, Γ ≈ 2.3 ± 0.2

- VERITAS / MAGIC / HESS campaign 2008: 120 h, 50 nights + 5 Chandra pointings
- VERITAS: ~45 h, ~7σ in 2008
- Outburst in February 2008 confirms day scale variability!
- Correlation to X-ray brightening in core: VHE likely not associated with HST-1
- VHE Emission has been predicted on a variety of time scales:
  - Prompt: would be an indication of extraordinarily relativistic bulk flows
  - Afterglow Emission: many models show a blazar-like SED
  - X-ray Flares: lots of seed photons available for IC scattering

- GRB observations take precedence over all other observations
- Response times of a few minutes
  - (best is 92 seconds)
- Observations of 22 GRBs less than 3 hrs old
  - 10 bursts satisfying Good Weather, High Elevation, No Moonlight
- 99% C.L. limits typically < 1-4% Crab

<table>
<thead>
<tr>
<th>GRB</th>
<th>T90</th>
<th>z</th>
<th>ΔT</th>
<th>IACTs</th>
<th>Limit (99% c.l.)</th>
<th>Time Interval (hh:mm:ss)</th>
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<td>070311</td>
<td>50 s</td>
<td>—</td>
<td>44.5 m</td>
<td>2</td>
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<td>070521</td>
<td>38 s</td>
<td>0.553?</td>
<td>18.6 m</td>
<td>3</td>
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<td>0:18:38 − 2:28:52</td>
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<td>—</td>
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<td>4</td>
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<td>0:04:41 − 1:50:44</td>
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</table>
Particle Astrophysics
Dark Matter

Three complementary approaches

- Produce neutralino in laboratory
- Only direct link between a neutralino and dark matter halo profiles
- Indirect detection of astrophysical $\gamma$-rays from DM self-annihilation

Fermilab Tevatron Large Hadron Collier
CDMS @ Soudan
COUPP Heavy Liquid Bubble Chamber

Directly detect DM WIMP in specialty detectors in (underground) labs
- Dwarf Galaxy Survey
- Extremely dark matter (DM) dominated objects
- “clean” source in γ-rays due to low star formation rate
- 1% Crab limits on Draco, Ursa Minor, Willman I
- Also: Local Group Galaxies and Galaxy Clusters
- Can have astrophysical motivations / backgrounds

Acciari et al., in preparation (2009)
Future Plans
VERITAS Upgrade

Baseline Plan:
- move T1 (20% sensitivity)
- Superbialkali (lower $E_{\text{thres}}$, sensitivity)
- upgrade trigger system: real-time $\gamma$/hadron separation, lower $E_{\text{thres}}$

Enhanced Plan:
- one additional telescope
- active mirror alignment system
Summary

- VERITAS Instrument is working extremely well
  - 95% uptime
  - excellent performance
  - meets predicted sensitivity
  - significant & cost effective upgrades

- first ~ 2 years of the VERITAS Science program successful
  - several source discoveries
  - many detections and multiwavelength campaigns
  - more results at the ICRC 2009 (Lodz)

- Science Highlights:
  - discovery of IBLs as a new class of blazars (GeV/TeV overlap)
  - extended TeV emission from SNR IC443
  - detailed studies of HMXB LS I +61 303
  - galactic plane survey of Cygnus region (results at ICRC)
  - radio galaxy M87: TeV/X-ray emission from core?

- VERITAS Science program is broad and also incl.
  - Dark Matter searches
  - GRB ToOs
Backup Slides
1ES 2344+514

- HBL
- $z = 0.044$
- DISCOVERED 1995 BY Whipple
- 0.07 Crab

VERITAS Observations Oct. 07 - Jan. 08
- 20.5 $\sigma$ detection
- Swift: highest known X-ray flux on Dec. 8 07
- VHE flux on Dec. 6/7 07: 0.41 Crab
Mrk 421

- HBL
- $z = 0.031$
- “OLD FAITHFUL”
- Early 2008:
  0.3 - 10 Crab
- TeV monitor of transients

ATEL#1506