Recent highlights from VERITAS

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Outline

• Very high-energy (VHE) gamma-ray astrophysics
• Ground-based observations with Cherenkov arrays
• VERITAS & instrument performance
• Highlights of some recent science results
  – Extragalactic sources: AGNs, Mrk 421 flaring
  – Galactic sources: Cygnus, CTA1, Tycho, Crab pulsar
  – Astroparticle physics: dark matter searches
• VERITAS Upgrade & Outlook
• Conclusions
Very high-energy (VHE) gamma-ray astrophysics

- At \( E > 50 \) GeV, several classes of sources known...
  - Galactic:
    - Supernova Remnants
    - Pulsar Wind Nebulae
    - Binary systems
  - Extragalactic:
    - Active Galactic Nuclei
    - Starburst galaxies
- ...or expected:
  - Gamma-Ray Bursts
  - Dark-matter annihilation.

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The scientific questions

• Origin of cosmic rays
  – What are the accelerators?
  – How do they work? To what energies?

• Understanding the nature of particle accelerators
  – What is being accelerated (electrons? protons?)?

• Astrophysical sources for fundamental physics
  – eg. can use AGN flares to look for effects of quantum gravity (if start times are well understood)

• Discovery space for new physics
  – eg. large mass reach for WIMPs
Ground-based VHE observations

- VERITAS uses the air-Cherenkov *imaging technique*: shower is imaged in multi-PMT cameras at focus of telescopes
- Arrays dramatically enhance sensitivity and resolution
- Effective area ~ size of light pool ~ $10^5$ m$^2$
VERITAS

VERITAS
• Four 12-m imaging air-Cherenkov telescopes
• Sited at Whipple Observatory, Az
• International collaboration (US, Canada, UK, Ireland, Germany)
  ~ 80 collaborators at 20 institutions
• Fully operational since 2007
• ~1000 observing hours/yr

Performance
• Energy range: 100 GeV → 30 TeV
• 3.5° field of view
• Angular resolution: < 0.1° (68% containment)
• Energy resolution: 15%-25%
• Sensitivity (5σ detection):
  – Crab Nebula: ~ 60 sec
  – 1% Crab Nebula flux: < 30 h

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The (current) VERITAS Sky

- As of May, 2011: 39 source detections:
  - Extragalactic: 22 (20 blazars, 2 non-blazars)
  - Galactic: 12 (9 PWN/SNR, 2 binaries, 1 pulsar)
  - Unidentified: 5

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Extragalactic observations

- Extragalactic objects make up majority of VERITAS sources
- Primarily blazars, mostly HBL
- Aim: understand jet production by supermassive black holes and the physics behind gamma-ray production
  - leptonic?
  - hadronic?
- Regular monitoring campaign on TeV blazars
- Multiwavelength campaigns important
- Major goal: measure the extragalactic background light (EBL) through its effect on blazar spectra
  \[ \gamma_{\text{TeV}} Y_{\text{EBL}} \rightarrow e^+e^- \]
Extragalactic results: the blazar list

<table>
<thead>
<tr>
<th>Source</th>
<th>Type</th>
<th>Redshift z</th>
<th>Discovery?</th>
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<tbody>
<tr>
<td>Markarian 421</td>
<td>HBL</td>
<td>0.031</td>
<td>Whipple</td>
</tr>
<tr>
<td>Markarian 501</td>
<td>HBL</td>
<td>0.034</td>
<td>Whipple</td>
</tr>
<tr>
<td>1ES 2344+514</td>
<td>HBL</td>
<td>0.044</td>
<td>Whipple</td>
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<td>1ES 1959+650</td>
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<tr>
<td>H 1426+428</td>
<td>HBL</td>
<td>0.129</td>
<td>Whipple</td>
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<td>1ES 1218+304</td>
<td>HBL</td>
<td>0.182</td>
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<tr>
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<td>0.138</td>
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<tr>
<td>W Comae</td>
<td>IBL</td>
<td>0.102</td>
<td>Y</td>
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<td>3C 66A</td>
<td>IBL</td>
<td>0.444 (?)</td>
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<td>RGB J0710+591</td>
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<tr>
<td>PKS 1424+240</td>
<td>IBL</td>
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<td>Y</td>
</tr>
<tr>
<td>RGB J0512.8+2112</td>
<td>HBL</td>
<td>unknown</td>
<td>Y</td>
</tr>
<tr>
<td>RBS 0413</td>
<td>HBL</td>
<td>0.190</td>
<td>Y</td>
</tr>
<tr>
<td>1ES 0502+675</td>
<td>HBL</td>
<td>unknown</td>
<td>Y</td>
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<tr>
<td>1ES 0229+200</td>
<td>HBL</td>
<td>0.140</td>
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<tr>
<td>RXS J0648.7+1516</td>
<td>HBL</td>
<td>0.179</td>
<td>Y</td>
</tr>
<tr>
<td>1ES 0414+009</td>
<td>HBL</td>
<td>0.287</td>
<td></td>
</tr>
<tr>
<td>PG 1553+113</td>
<td>HBL</td>
<td>unknown (&gt;0.43)</td>
<td></td>
</tr>
<tr>
<td>1ES 1440+122</td>
<td>IBL</td>
<td>0.162</td>
<td>Y</td>
</tr>
<tr>
<td>1ES 1215+303</td>
<td>HBL</td>
<td>0.130 (?)</td>
<td></td>
</tr>
</tbody>
</table>

- Several blazars at z>0.18
- Will allow strong constraints on EBL
## Extragalactic results I: AGN discoveries

### RBS 0413
- ~5.5σ in 25 h
- 1.6% Crab Nebula
- X-ray-bright HBL \( @ z=0.19 \)
- brightest LAT extrapolation
- ATEL #2272 with Fermi

### RX J0648.7+1516
- ~5.2σ in 18 h
- 2% Crab Nebula
- Keck: Blazar
- \( z=0.179 \) (Lick 3m)
- ATEL #2486

### VER J0521+211 (RGB J0521.8+2112)
- ~4% Crab Nebula
- \( z=? \) (unsuccessful MMT, MDM, IR efforts)
- bright flare (>20% Crab)
- ATELs #2260 & #2309

### 1ES 0414+009
- ~7σ in 45 h; 2% Crab
- among X-ray-brightest HBL
- \( z=0.287 \)
- EBL! high-z Mkn 421
- H.E.S.S. detection

### 1ES 0502+675
- ~12σ in 30 h
- 5% Crab Nebula
- \( z\neq 0.341 \)? (1h MMT exposure – no features, no redshift)
- ATEL #2301

### 1ES 1440+122
- ~5.2σ in 50 h
- <1% Crab Nebula
- hard-spectrum IBL (LAT)
- \( z=0.162 \)
- ATEL #2786
Extragalactic results II: the first triple-AGN field!

"Make that a trio…"

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Extragalactic results III: Mrk 421 flaring

- Regular monitoring allows detections of flares
  - Deep observations and multiwavelength campaigns
- Ex.: Markarian 421 (Feb 2010) – flared to > 10x Crab Nebula
- Strong enough to allow 2-minute binning!
- Spectral-evolution studies in progress
Galactic observations

- Extensive targeted observations as well as Sky Survey (Cygnus region)
- 13 sources observed to date
- Several galactic source types: SNR, PWN, binary systems, pulsar

Galactic center: see talk by M. Beilicke this PM
Galactic observations (Cygnus survey)

- 112 hr base survey (+56 hrs follow-up)
- Depth: <3% Crab Nebula flux (E>200 GeV, point sources)
Galactic results I: VER2019+407 & γ-Cygni

- G78.2+2.1 (gamma-Cygni): SNR of age 5-10 kyr
- VERITAS: 18.6 hrs (2009)
- Detection: 9.6σ (7.5σ post-trials): VER2019+407
- Extended emission: σ ~ 0.18°±0.4

- Likely emission from SNR acceleration, then collision with ambient material
- Partial HI shell to NW may suggest hadronic emission

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Galactic results II: The Cygnus region

- Region seen as extended source (multiple sources?) by Milagro at E>10 TeV (90% Crab flux at E>20 TeV)
- VERITAS data: 75 h (summer/fall 2010)
Galactic results II: Cygnus region

• Complicated region!
  – radio- and gamma-ray pulsar PSR J2021+3651
  – PWN CTB 87
  – several WR stars
  – several EGRET sources

• VERITAS: 75 hrs of data (2010)
• Search for both point and extended emission; see two new sources:
  – CTB 87 (PWN)
  – Cyg OB1 complex
Galactic results IIa: CTB 87

- VERITAS sees point source coincident with CTB 87
- Detection at 6.1σ
- Flux at E> 1 TeV: ~ 0.8% of Crab Nebula
- Power-law spectrum (Γ ~ 2.1±0.5), lack of variability
- Nearby blazar (BS 2013+370) excluded as TeV source at 99% CL
Galactic results IIb: Cyg OB1 region

- VERITAS extended-source analysis sees broad emission region
- Detection at 8.3σ (7.4σ post-trials)
- Coincident with MGRO J2019+37
- Multiple sources likely – need more data!
Galactic results III: CTA1

- young SNR (~13 kyr)
- composite SNR: radio shell, center-filled X-ray emission
- Fermi & X-ray (XMM-Newton) pulsar
- VERITAS data:
  26.5 hr (2010-2011 season)
Galactic results III: CTA1

- VERITAS detection: 7.3σ (6.3σ post-trials)
- Flux (E > 1 TeV): ~4% of Crab Nebula
- Extended emission
Galactic results III: CTA1

- VERITAS contours: green
- Fermi pulsar: red circle
- Radio (1420 MHz) contours: black

- Consistent with young PWN: new TeV source
Galactic results IV: Tycho’s SNR (G120.1+1.4)

- Type 1A SN, observed in 1572
- VERITAS data: 68 hr (2008, 2010)
- Detection: 5.0σ (post-trials)
- Flux (E > 1TeV): 0.9% of Crab Nebula
- Power-law spectrum: \( \Gamma = 1.95 \pm 0.5 \pm 0.3 \)
- Peak significance close to where molecular cloud is interacting with SNR
- Both leptonic and hadronic models fit data
Astroparticle observations: Dark Matter Searches

- Dark matter ~25% of energy density of Universe
- Must be non-baryonic, cold, heavy, gravitationally bound
- WIMPs (eg. neutralino) in 50 GeV – 10 TeV range are well-motivated candidates
- Self-annihilation could lead to GeV/TeV gamma signal
- Cherenkov arrays well suited for this search
Astroparticle observations: Dark Matter Searches

- Good targets are nearby galaxies with high mass-to-light ratios:
- Candidates: dwarf spheroidals (small astrophysical backgrounds)
- Ursa Minor, Draco, Willman I, Bootes I, Segue 1
Astroparticle results: Dark Matter Searches

- eg: Ursa Minor
- ~20 hrs data; no detection
- Flux limit: 1-2% Crab Nebula (95%)
  \(0.4 \times 10^{-12} \text{ cm}^{-2}\text{s}^{-1}\)
- Turning flux limit into DM limit needs
  - Particle-physics modeling
  - Astrophysical factor \(J\) (DM density distribution squared), \(\sim 10^{18} \text{ GeV}^2\text{cm}^{-5}\)
- Usually use NFW profile
  (Segue 1: Einasto profile)
Astroparticle: Dark Matter Searches

- VERITAS limits on $<\sigma v> \sim 10^{-23}$ cm$^{-3}$s$^{-1}$
- Need significant astrophysical boost factor to constrain models
The future: VERITAS Upgrades

• FPGA-based Trigger upgrade (partially installed, commissioning underway)
  – improved CR event rejection

• PMT replacement with high-efficiency PMTs (summer 2012, funded)
  – ~50% increase in QE over current tubes
  – lower energy threshold (trigger threshold to < 100 GeV)
  – improved sensitivity

• LIDAR System (2011, funded)
  – Improved atmospheric monitoring

• Telescope drive upgrade (study phase)
  – shorter response time to GRBs, etc.
VERITAS PMT upgrade

Hamamatsu R9800
(QE and PDE measurement: WashU and UCSC )

simulation of gamma-ray response
Conclusions

• VERITAS operating well, improved sensitivity since 2010
• Many new sources and exciting results on known sources
• Active collaboration with other VHE instruments, Fermi/LAT and instruments at other wavelengths
• Upgrade underway w/several years of stable operation following