Very-High-Energy Emission from Extragalactic Cosmic Accelerators:

Highlights from Recent VERITAS AGN Observations

Qi Feng for the VERITAS Collaboration — Oct 2018
Extragalactic Cosmic Accelerators

Multiwavelength astronomy
VERITAS/Fermi-LAT VLBA (SMBH Jet)

Multi-messenger Astronomy:
Gamma-ray emission entangled to CR emission

VERITAS
Fermi
IceCube

Cosmic Rays
Gamma Rays $\gamma$
Neutrinos $\nu$

EBL: Extragalactic background light

$$\pi^0 \rightarrow \gamma + \gamma$$

$$\pi^\pm \rightarrow \mu^\pm + \nu$$

$$\mu^\pm \rightarrow e^\pm + \nu$$

$$p^+, \alpha^{2+}, \ldots, e^-$$

VERITAS

Fermi-LAT

VLBA

SMBH Jet

ICE CUBE

Multiwavelength astronomy
VERITAS/Fermi-LAT VLBA (SMBH Jet)
VERITAS Observatory Overview

- Study very-high-energy (~85 GeV to ~30 TeV) \( \gamma \)-rays from astrophysical sources
- Full-scale operations since 2007; Major upgrade completed in 2012
- Good-weather data / yr: \(~950\) h in “dark time” + \(~250\) h in “bright moon” (illum. \(>30\%\))

  - Sensitivity: 1\% Crab in \(<25\) h
  - Angular resolution: \(\theta_{68} \sim 0.08^\circ\) @ 1 TeV
  - Energy resolution: \(~17\%\)
  - Energy Threshold: \(~85\) GeV
  - Spectral reconstruction > 100 GeV
  - Systematic errors: Flux \(~20\%\); \(\Gamma \sim 0.1\)
The **Extragalactic very-high-energy (VHE) sky** (TeVCat as of Oct 2018):

- 10 LBL/IBL
- 50 HBL
- 4 Blazar Type Uncertain
- 7 FSRQ
- 4 FRI (RG)
- 2 Starburst

\[
\begin{align*}
\text{77 AGN - number comparable EGRET AGN catalogue} \\
\text{39 VERITAS AGN} \\
\text{VERITAS detections since June 2017:} \\
\text{TXS 0506+056, 3C 264, and Ton 599}
\end{align*}
\]
TeV gamma-ray variability is amazing!
TXS 0506+056: The "Neutrino Blazar"

See Azadeh Keivani’s talk

- BL Lac (IBL), $z = 0.34$
- Multi-messenger effort to search for cosmic hadron accelerators.
- Multiple alerts following the IceCube event IC170922A:
  +6 days *Fermi* ATel #10791: $\sim 6x$ 3FGL flux
  +12 days MAGIC ATel #10817: VHE detected
  +17 days VERITAS ATel #10833: 5.5-h of data in two weeks **starting 12.2 hours after** the event led to **no detection**…
- VERITAS kept observing until Feb 2018 (+5 months), 35-h data led to a detection of possibly the **base line flux**
- $F(>110$ GeV) $\sim 1.6\%$ Crab; Soft VHE spectrum: $\Gamma = 4.8 \pm 1.3$; sharp spectral cutoff cannot be accounted for by EBL alone.
3C 264 - The Newest VHE Radio Galaxy

- Radio galaxy (FR I), $z = 0.0217$
- VERITAS detection in 2018 (ATel #11436)
- Strong, hard-spectrum detection:
  $\sim 8\sigma$ in $\sim 44$ h; $\Gamma \sim 2.3$
- Low, weakly variable VHE flux:
  $\sim 0.5\%$ Crab; $\sim$Month-scale variations
- The misaligned jets in radio galaxies are unique laboratory for understanding their structures.
- Jet $< 1$ kpc, multiple superluminal knots
- Major VERITAS + MWL effort: Radio (e.g. VLA), Optical (HST, ground-based), X-ray (Chandra + Swift), Fermi-LAT =>

No major activity in knots or core

*Do NOT use preliminary results presented here in any presentation or publication without contacting the VERITAS team.

See Eileen Meyer’s talk
BL Lacertae
Fast TeV Flares Coincident With Emergence of a Radio Knot

- IBL, $z = 0.069$
- Fast flares constrain the size of the emitting region
  - Peak: $\sim$125% Crab; Exp. decay: $\tau_d = 13 \pm 4$ min
  - Associated w/ birth of superluminal radio knot
- Two, single-night flares in 2015 (16% & 9% Crab)

- Major flare on Oct. 5, 2016
- Peak flux $\sim$180% Crab
- Slow rise ($t_{\text{rise}} \sim 140$ min) & rapid fall ($t_{\text{decay}} \sim 36$ min $\Rightarrow < 12 \, R_{\text{Schwarzschild}}$)
- Another candidate superluminal knot appears

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Faster flow of plasma/perturbation
Particle dominated jet
Magnetic dominated jet
Magnetic reconnection - gamma-ray flare

IBL, z = 0.069

Radio core/stationary knot
Stationary knot
Superluminal knot

Fast flares constrain the size of the emitting region
Mrk 421: Fast Flares during a Major Outburst

- HBL, \( z = 0.031 \)
- Iconic TeV blazar with many flares at all wavelengths
- A major flare in 2010 with multiple sub-hour TeV gamma-ray flares (peak >10 Crab)
- Fast variability on timescales of \(~17\) min \(\Rightarrow\) emitting size < a few Schwarzschild radii
- TeV gamma-ray and X-ray spectral variability compared

\[ >110 \text{ GeV} \]
\[ t_r = 32/17 \text{ min} \]
\[ t_d = 34/47 \text{ min} \]
\[ >20,000 \text{ photons within 2 hrs} \]
\[ >10 \text{ sigma in each 2-min bin} \]
• $HBL, z = 0.131$

Evidence for a long-term increase in GeV and optical flux

• An extreme shift of synchrotron peak frequency from low state to flaring state ($IBL \rightarrow HBL$)

• Stationary radio knots in the innermost jet region in VLBA data (typical HBL)

Time-resolved modelling of the SED using "blob-in-jet" SSC model => flaring state is likely associated with a more efficient adiabatic cooling

1ES 1215+303: 10 Years of Fermi and VERITAS Data

See Janeth Valverde’s poster

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Fermi + VERITAS Collaboration, 2018, in prep
OJ 287: a VERITAS VHE Discovery

Optically bright blazar, \( z = 0.306 \)
Classification uncertain; HBL-like SED
TeV candidate: Costamante & Ghisellini 2002

"Periodic" optical behavior: \( T \sim 12 \) yr
The best candidate for binary SMBH system?
Optical thermal flares, disk crossing (Hudec 2017)?
Jet precession (Britzen+ 2018)?
Next optical outburst in 2019

VERITAS limit in 2007: 10 h, <2.6% Crab
Swift XRT flaring => 2016-17 ToO

VHE discovery in Feb 2017:
ATel #10051

2016-17: \( \sim 50 \) h, \( 9.7 \sigma \), \( \Gamma = 3.49 \pm 0.28 \)
\( F(>150 \text{ GeV}) = (4.61 \pm 0.61) \times 10^{-12} \text{ cm}^{-2} \text{s}^{-1} \); 1.3% Crab

Copious MWL data: SED shifts
Possible contemporaneous birth of a radio knot near BH

Project VLBA-BU-BLAZAR (Marscher, Jorstad)

Qi Feng for the VERITAS Collaboration — Oct 2018
Ton 599: The Third Highest $z$ VHE Source

See Ari Brill's poster

- **FSRQ, $z = 0.72$**
- Fermi-LAT flare in early Nov. 2017
- ATel #10931: $\sim 20 \times$ 3FGL flux
- Exceptional NIR flares in Nov. 2017
- ATel #10949: 0.5 mag. after 10x flux

VERITAS' 3rd FSRQ & 7th in VHE

PKS 1441+25 ($z \sim 0.94$) & 4C +21.35 ($z \sim 0.43$)
TeV photons provide cosmological constraints!
Constraints on Extragalactic Background Light with VERITAS Blazar Observations

- Interaction of EBL-VHE photons results in attenuation above 100 GeV
- VERITAS long term program on extreme blazars exhibiting high-energy spectrum with no evidence of a cutoff up to a few TeV
- Model-independent upper limits on EBL spectrum from 8 VERITAS blazars => galaxy surveys have resolved most of the sources of the EBL at these wavelengths
- VERITAS fills a unique niche with observations of extreme blazars at nearby to moderate redshift (0 < z < 0.3), great for probing the longer wavelength EBL, complimentary to Fermi-LAT, with better sensitivity than HAWC
**Constraints on Intergalactic Magnetic Field with VERITAS Blazar Observations**

- For IGMF $10^{-16}$ G — $10^{-12}$ G, pair halos for blazars ($z: 0.1 - 0.2$) are detectable by current IACTs
- Tested for extended emission around 7 hard-spectrum blazars
- No deviation from simulated instrument PSF
- Exclude IGMF strengths around $\sim 10^{-14}$ G at 95% confidence level


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**Table 1:**

<table>
<thead>
<tr>
<th>Source name</th>
<th>Event counts</th>
<th>$\chi^2_{(MC - data)/\sigma}$</th>
<th>$\theta_2$</th>
<th>$\theta_2$ $B$ [G]</th>
<th>$\Gamma$</th>
<th>$w_{data}$</th>
<th>$w_{sim}$ 68% containment</th>
<th>$w_{sim}$ 95% containment</th>
<th>$95%$ CL UL on $f_c$</th>
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</thead>
<tbody>
<tr>
<td>1ES 1218+304</td>
<td>0.108</td>
<td>1.923</td>
<td>0.025</td>
<td>0.4502</td>
<td>0.003</td>
<td>0.038</td>
<td>0.3481</td>
<td>0.05</td>
<td>0.038</td>
</tr>
<tr>
<td>PG 1553+113</td>
<td>0.139</td>
<td>2.025</td>
<td>0.045</td>
<td>0.034</td>
<td>0.52</td>
<td>0.150</td>
<td>0.3634</td>
<td>0.06</td>
<td>0.150</td>
</tr>
<tr>
<td>Mrk 501</td>
<td>0.034</td>
<td>1.716</td>
<td>0.085</td>
<td>0.1586</td>
<td>0.95</td>
<td>0.024</td>
<td>0.1389</td>
<td>0.08</td>
<td>0.024</td>
</tr>
<tr>
<td>Mrk 421</td>
<td>0.031</td>
<td>1.772</td>
<td>0.024</td>
<td>0.0990</td>
<td>0.31</td>
<td>0.016</td>
<td>0.2269</td>
<td>0.06</td>
<td>0.016</td>
</tr>
</tbody>
</table>

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**Figure 1:**

Event counts vs. $\theta_2$ for 1ES 1218+304 and Simulation.

**Figure 2:**

Comparison between the angular profiles of Mrk 501 and 1ES 1218+304.

**Figure 3:**

The left panel shows the dependence of the width of the simulated angular distribution on significance. Column 6: Number of excess events. Column 7: VERITAS detection.
TeV gamma-ray variability is amazing!

- VERITAS observations are revealing the processes of cosmic-ray acceleration and transport
- Multi-messenger programs are opening new windows into extreme environments
  - VERITAS detection of TXS 0506+056 following IceCube HE neutrino alert: more deep campaigns coming
- Probe the location & mechanism of gamma-ray emission & connection with radio activity:
  - Radio galaxy flares (3C 264, NGC 1275, MWL observations)
  - Fast variability: IBL/LBL (BL Lac, VLBA; Mrk 421)
  - SMBBH OJ 287 detection (not disk crossing, but jet activity)
- MWL observation of flares allow broadband SED modelling, VERITAS data constrain the highest-energy particles.
- Indirect measurement of EBL and IGMF with gamma-ray observations continue to provide new constraints on the gamma-ray propagation in cosmology context

- We are always looking to collaborate! https://veritas.sao.arizona.edu/
  - External proposals are welcome!
Backup slides
Radio galaxy (FR I) in the center of Perseus Cluster, $z = 0.0176$

- Multiple flares in 2016 and 2017
- Brightest-ever VHE radio galaxy detection in 2017. (flux $\sim$50% Crab), but no intra-night variation
- Significant spectral hardening: $\Gamma \sim 2.75$; c.f. $\Gamma \sim 4.1$ prior to 2016-17

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VERITAS detected M82 in 2009
Among weakest-ever VHE sources, 0.9% Crab
No clear determination of the origin of the VHE emission

VERITAS has since undergone two upgrades
The exposure on M82 has increased: ~137 hours → ~240 hours
We have deployed new analysis methods
An update on M82

- Post-camera upgrade data allow lowering the energy threshold
- Image template method and boosted decision trees offer a remarkable improvement over standard analysis
- Much tighter $\theta^2$ cut of 0.006 deg$^2$ vs 0.01 for standard analysis

- New results consistent with the published ones within errors
- Total flux at the lower end of the published value – even weaker than initially estimated
- Analysis ongoing
GRB 150323A

“A strong limit on the very-high-energy emission from GRB 150323A”