VERITAS Observations of the Cygnus Region

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Summary

❖ The Cygnus region & VERITAS
❖ Data and analysis
❖ Whole region results - VERITAS & *Fermi*-LAT
❖ Individual source results
❖ Comparison with other surveys
❖ Conclusions
The Cygnus Region

- Looking along spiral arm at local region of star formation.
  - Cosmic ray sources and target material.
- Closer to Sun than Galactic Center.
  - Sensitive to less luminous sources.
- Well studied at multiple wavelengths.
Observations with VERITAS

- 4 Telescope Operation since 2007
- ~1000 hours/yr in “dark time” observation
- ~300 hours/yr of bright moonlight data (>30%)

Telescope Moved 2009

Telescope

12m

~120m

499 PMTs

PMTs Replaced 2012

Energy Range: ~85 GeV - 30 TeV
Cygnus Observations

VERITAS analysis:
❖ 15° by 5° area centered (l, b) = (74.5°, 1.5°).
❖ 135 hours initial survey (sensitive to a point source of strength 4% of the Crab Nebula).
❖ 175 hours targeted observations on known sources, potential sources and survey identified hotspots.
❖ Data prior to 2012 upgrades.
❖ “Point” and “Extended” analyses with cuts tuned for hard spectrum, galactic region sources.

Fermi-LAT analysis:
❖ > 1 GeV, Pass 8, SOURCE class to reduce galactic diffuse/pulsar contribution & improve point spread function.
❖ 7 years of data (2008 August - 2016 January).
❖ Off pulse and “fixed on pulse” searches for pulsar wind nebulae.
❖ Input model based on 3FGL but cross checked with 1FHL and 2FHL.

Exposure Map

Gamma Cygni (VER J2019+407)
TeV J2032 +4130 (VER J2031+415)
CTB 87 (VER J2016+371)
VER J2019+378 (MGRO J2019+37)
Whole Region - VERITAS (Extended)
Whole Region - *Fermi*-LAT

Cygnus X-1

Cygnus X-3

G73.9+0.9

2HWC J2006+341

VERITAS ICRC 2017
TeV J2032+4130 (VER J2031+415)

- **VERITAS:**
  - Extended emission detected at 10.1σ.
  - Asymmetric Gaussian fit - 0.19±0.02° by 0.08±0.01°
  - 
    \[(2.05 \pm 0.42) \times 10^{-16} (E/1820 \text{ GeV})^{-2.03\pm0.37} \text{ GeV}^{-1} \text{ cm}^{-1} \text{ s}^{-1}\]

- **Fermi-LAT:**
  - Off-pulse and “Fixed on-pulse” analysis showed extended residual
  - Fit with 0.15°±0.02° Gaussian, TS = 321.1, TS extension = 28.6
  - 
    \[(1.44 \pm 0.09) \times 10^{-9} (E/2.27 \text{ GeV})^{-2.27\pm0.07} \text{ GeV}^{-1} \text{ cm}^{-1} \text{ s}^{-1}\]

Emission occurs in void in gas (Aliu 2014)

- Pulsar wind nebula?
  - No spectral break.
  - PSR J2032+4127 is in a long period binary.
  - This doesn’t explain extended emission.
Gamma Cygni (VER J2019+407)

- **VERITAS:**
  - Extended emission detected at 7.6σ
  - Asymmetric Gaussian fit - 0.29±0.02° by 0.19±0.01°
  - \((5.01 \pm 0.93) \times 10^{-16} (E/1500 \text{ GeV})^{-2.79\pm0.39} \text{ GeV}^{-1} \text{ cm}^{-1} \text{ s}^{-1}\)

- **Fermi-LAT:**
  - Emission shows similar structure with excess in location of VERITAS source.
  - Emission from region coincident with VERITAS emission agrees well.
    - Constant index across remnant, enhancement in flux.

- Enhanced emission from northern rim in both Fermi-LAT and VERITAS.
- Fermi-LAT morphology matches radio morphology of supernova remnant.
- Fermi-LAT and VERITAS spectra show good match.
- HAWC position offset?
VER J2019+368 (MGRO J2019+37)

- **VERITAS:**
  - Extended source detected at $10.3\sigma$.
  - Fit with an asymmetric Gaussian $0.34\pm0.02^\circ$ by $0.14\pm0.01^\circ$.
  - $(1.02 \pm 0.11) \times 10^{-16} \times (E/3110 \text{ GeV})^{-1.98\pm0.09} \text{ GeV}^{-1} \text{cm}^{-1} \text{s}^{-1}$

**VERITAS Significance**

**VERITAS ICRC 2017**

**HAWC from Abeysekara 2017**
VER J2019+368 (MGRO J2019+37)

- **VERITAS:**
  - Extended source detected at $10.3\sigma$.
  - Fit with an asymmetric Gaussian $0.34\pm0.02^\circ$ by $0.14\pm0.01^\circ$.
  - $(1.02 \pm 0.11) \times 10^{-16} \times (E/3110 \text{ GeV})^{-1.98\pm0.09} \text{ GeV}^{-1} \text{cm}^{-1} \text{s}^{-1}$
- **Point Analysis:**
  - Two hotspots $>7\sigma$ with a valley ($\sigma < 4$) between them.
  - Two new sources:
    - VER J2018+367
    - VER J2020+368
Point Analysis → Two Sources

- VER J2018+367
  - 7.8σ
  - Symmetric Gaussian fit - 0.18±0.01°
  - \((5.12 \pm 0.94) \times 10^{-17} \times \frac{(E/2710 \text{ GeV})^{-2.00\pm0.21}}{\text{GeV}^{-1}\text{cm}^{-1}\text{s}^{-1}}\)

- VER J2020+368
  - 7.2σ
  - Symmetric Gaussian fit - 0.03±0.01°
  - \((3.00 \pm 0.56) \times 10^{-17} \times \frac{(E/3270 \text{ GeV})^{-1.71\pm0.26}}{\text{GeV}^{-1}\text{cm}^{-1}\text{s}^{-1}}\)

- Could be hotspots in larger source or two partially resolved sources (or a combination).

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Multiwavelength View

- No evidence of pulsar wind nebulae in *Fermi*-LAT data from either of the pulsars.
- **VER J2018+367:**
  - *NuSTAR* (Gotthelf 2016) observations show a number of sources to the west.
  - Nothing in *Suzaku* observations.
  - *IGR J20188+3647* still the only real candidate in the region (supergiant fast X-ray transient) but extended emission?
- **VER J2020+368:**
  - *Suzaku* (Mizuno 2017) observations show PWN stretching from 3FGL J2021.1+3651 towards it, but centroid lies beyond this, possible counterpart?

Red: $>1000\text{GeV}$, 0 - 70 counts
Green: $<1000\text{ GeV}$, 0 - 30 counts
CTB 87 (VER J2016+371)

- **VERITAS:**
  - Point source detected at 6.2σ.
  - \((2.8 \pm 1.2) \times 10^{-16}(E/2510 \text{ GeV})^{-2.1\pm0.8}\text{ GeV}^{-1}\text{cm}^{-1}\text{s}^{-1}\)

- **Fermi-LAT:**
  - Is observed source CTB 87, QSO J2015+371, or combination of both?
  - Add sources at both locations, CTB 87 located source has better spectral match with VERITAS data.
  - Likely observed emission is combination of both thus far unresolved.

- Fermi-LAT detecting emission from both CTB 87 and QSO J2015+371.
- Spectra form VER J2016+371 and CTB 87 located Fermi-LAT source show good agreement.
  - Common origin, CTB 87.
## Comparison with H.E.S.S. Galactic Plane Survey

- Compare number of sources in H.E.S.S. galactic plane survey with the number seen in this analysis.
  - Using data from H.E.S.S. Galactic Plane Survey
    - Survey region = $250^\circ < l < 65^\circ$, $-3.5^\circ < b < 3.5^\circ$, 2800 hours
    - 56 sources @ average sensitivity of approximately 2% Crab Nebula flux.
  - Use *Fermi*-LAT catalogs to predict number of VERITAS sources in survey region.

<table>
<thead>
<tr>
<th>Comparison Catalog</th>
<th>Number of Sources in VERITAS region</th>
<th>Number of Sources in H.E.S.S. Region</th>
<th>Predicted Number of VERITAS Sources</th>
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<tbody>
<tr>
<td>3FGL</td>
<td>37</td>
<td>339</td>
<td>6</td>
</tr>
<tr>
<td>2FHL</td>
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<tr>
<td>3FHL</td>
<td>13</td>
<td>119</td>
<td>6</td>
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</table>
Conclusions

Examined a a 15° × 5° area centered (l , b) = (74.5°, 1.5°) using 309 h of VERITAS data and over 7 years of Fermi-LAT data above 1 GeV.

❖ **VER J2031+415:** An extended Fermi-LAT counterpart to VER J2031+415 (TeV J2032+4130) is detected at a test statistic of 321.

❖ **VER J2019+407:** 3FGL J2021.0+4031e is not a uniform disk, rather, it peaks at the north eastern rim, in the same region as the VERITAS emission and their spectra match.

❖ **VER J2019+368:** Is resolved into two sources, VER J2018+367 and VER J2020+368. Both sources are detected at a level greater than 7σ. No counterparts seen for VER J2018+367. VER J2020+368 may be associated with an X-ray pulsar wind nebula.

❖ **VER J2016+371:** The Fermi-LAT emission may be due to two unresolved point sources. A single power law fits the data from the CTB 87 located Fermi-LAT source and the emission detected by VERITAS.