VERITAS detection of VHE emission from the optically bright quasar OJ 287

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For The VERITAS Collaboration
1. OJ 287
2. Historical Observations and Monitoring Programs
3. VERITAS Observations
4. Fermi-LAT and Swift-XRT Observations
5. Multiwavelength Results
6. Conclusions and Future Plans
• Optically bright quasar located at $z = 0.306$.
• Classification unclear (LBL/FSRQ).
• Archival observations dating back to 1890 reveal a ~12 year outburst cycle.
• Models invoking a binary black hole system and a helical jet have been used to explain quasi-periodic nature.
• Valtonen et al. 2011 using a BBH model accurately predicted 2007 and 2015 optical outbursts.
• Optical outburst expected in 2019!
Previous Observations and Monitoring

- Previously observed by VERITAS (S. Archambault et al. 2016):
  - During anticipated 2007 optical outburst
  - During 2010-2011 season
  - Non-detections, 99% c.l. upper limit of 2.6% Crab
- Observed by MAGIC during 2007 (H. Seta et al. 2009):
  - Non-detections and 95% c.l. upper limits of 3.3% and 1.7% Crab
- Regularly monitored by Swift-XRT as part of γ-ray ‘sources of interest’ program (M. C. Stroh et al. 2013):
  - Exceptional X-ray activity observed in late 2016
  - Intense MWL monitoring
Fermi-LAT: https://fermi.gsfc.nasa.gov/ssc/data/access/lat/msl_lc/

Swift-XRT: http://www.swift.psu.edu/monitoring/
Published VERITAS Observations

2010-2011 Season

Orbit of secondary black hole

Anticipated 2007 active phase

Primary accretion disk

Impact outflow

Primary spin direction


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• Exceptional X-ray activity this season lead VERITAS observations during December 2016 and January 2017.
• No detection!
• Historic X-ray rates observed by Swift-XRT.
• VERITAS initiated a ToO on 1\(^{st}\) - 4\(^{th}\) of February, triggering additional Swift-XRT observations.
• > 5\(\sigma\) detection, ATel released on 5\(^{th}\) of February.
• Intense VERITAS follow-up observations taken between 16\textsuperscript{th} February and 30\textsuperscript{th} March.
• Many observations taken simultaneously with Swift.
• ~50 hours of data (post quality cuts and dead time corrected) taken from 9th December 2016 – 30th March 2017.
• Data analysed using Boosted Decision Tree Gamma/Hadron cuts optimised for a soft spectrum source.
• Total of 3178 on-source and 15734 off-source events (normalisation of 0.167)
• 9.7σ detection.
• Time-averaged flux (E > 150 GeV) 1.3 % Crab.
• 2D symmetric gaussian fit applied to excess counts map, fit source location (J2000):
  - R.A. 08h 54'49.1" ± (2.2'')_{stat}, Dec:+20°05'58.89'' ± (31.96'')_{stat}

**VERITAS Results**

VERITAS data is divided up into 3 periods of approximate constant signal.

<table>
<thead>
<tr>
<th>Period (MJD)</th>
<th>Exposure (Hours)</th>
<th>Excess Significance (σ)</th>
<th>( F(E &gt; 150 \text{ GeV}) \times 10^{-12} ) [cm(^{-2})s(^{-1})]</th>
<th>( F(E &gt; 150 \text{ GeV}) ) [% Crab*]</th>
<th>( \chi^2/\text{NDF} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Before Historic Swift Flare</td>
<td>57731 – 57777</td>
<td>5.0</td>
<td>2.0</td>
<td>&lt; 7.64</td>
<td>&lt; 2.1</td>
</tr>
<tr>
<td>Enhanced X-ray activity</td>
<td>57785 – 57817</td>
<td>25.3</td>
<td>10.1</td>
<td>(6.51 +/- 0.93)</td>
<td>(1.8 +/- 0.3)</td>
</tr>
<tr>
<td>Decaying X-ray activity</td>
<td>57827 – 57843</td>
<td>20.1</td>
<td>2.8</td>
<td>(2.58 +/- 0.91)</td>
<td>(0.7 +/- 0.2)</td>
</tr>
<tr>
<td>Total</td>
<td>50.4</td>
<td>9.7</td>
<td>(4.61 +/- 0.62)</td>
<td>(1.3 +/- 0.2)</td>
<td>44.0/31</td>
</tr>
</tbody>
</table>

* A. M. Hillas et al. (1998)
VERITAS Results

- Total time-averaged spectrum obtained between 100 – 560 GeV.
- 95% c.l. upper limits calculated for < 5 on-source counts and < 2σ excess
- 1σ confidence interval on power-law fit (statistical errors only).

\[
\frac{dN}{dE}_{\text{obs}} = N \left( \frac{E}{E_0} \right)^{-\Gamma}
\]

<table>
<thead>
<tr>
<th>Period</th>
<th>(N \times 10^{-11}) [cm(^{-2})s(^{-1})TeV(^{-1})]</th>
<th>(E_0) [TeV]</th>
<th>(\Gamma)</th>
<th>(\chi^2 / \text{NDF})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total</td>
<td>((2.82 \pm 0.34_{\text{stat}}))</td>
<td>0.2</td>
<td>((3.49 \pm 0.28_{\text{stat}}))</td>
<td>0.5 / 3</td>
</tr>
<tr>
<td>(2) 57785 – 57817</td>
<td>((3.90 \pm 0.51_{\text{stat}}))</td>
<td>0.2</td>
<td>((3.58 \pm 0.32_{\text{stat}}))</td>
<td>0.25 / 3</td>
</tr>
</tbody>
</table>
VERITAS Results

\[ \frac{dN}{dE}_{\text{obs}} = \frac{dN}{dE}_{\text{intrinsic}} e^{-\tau(E,z)} \]

- \( z = 0.306 \rightarrow \text{significant EBL attenuation!} \)
- Observed spectrum is deabsorbed for EBL attenuation (assuming a Franceschini et al. 2008 EBL model)
- \[ \frac{dN}{dE}_{\text{deab}} = (4.66 \pm 0.56) \times 10^{-11} \left( \frac{E}{0.2 \text{TeV}} \right)^{-2.36 \pm 0.36} \text{ [cm}^{-2}\text{s}^{-1}\text{TeV}^{-1}] \]
- \[ \chi^2_{NDF} = \frac{0.6}{3} \]
### Fermi-LAT Results

<table>
<thead>
<tr>
<th>Period (MJD)</th>
<th>Test Statistic (TS)</th>
<th>$F(0.1$-$300$ GeV) ($\times 10^{-8}$) [$cm^{-2}s^{-1}$]</th>
<th>Spectral Index</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1) 57731 – 57777</td>
<td>122.5</td>
<td>(3.97 ± 1.07)</td>
<td>(1.90 ± 0.13)</td>
</tr>
<tr>
<td>(2) 57785 – 57817</td>
<td>100.9</td>
<td>(5.01 ± 1.44)</td>
<td>(1.96 ± 0.16)</td>
</tr>
<tr>
<td>(3) 57827 – 57843</td>
<td>95.8</td>
<td>(4.78 ± 1.89)</td>
<td>(1.75 ± 0.19)</td>
</tr>
<tr>
<td>3FGL</td>
<td>8.41*</td>
<td></td>
<td>(2.12 ± 0.03)</td>
</tr>
</tbody>
</table>

* Assuming 3FGL fit holds over (0.1-300 GeV)
Swift-XRT Results

- Swift-XRT analysis is ongoing.
- Analysis of Period 2 shows clear flux variability ($\chi^2/\text{NDF} = 156.7/18$).
- Spectral shape consistent with a constant model for Period 2 ($\chi^2/\text{NDF} = 11.22/18$).

X-ray Flux (2 keV – 10 keV)

Power-Law Index

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Swift-XRT Results

- Spectra obtained for the **hardest and brightest** and **softest and dimmest** observations during Period 2.

\[ \text{Index} = 2.59 \pm 0.06, \text{Flux} = (1.04 \pm 0.05) \times 10^{-11} \]

\[ \text{Index} = 2.70 \pm 0.13, \text{Flux} = (4.10 \pm 0.47) \times 10^{-12} \]
Multiwavelength Light Curves

VERITAS Time-Averaged Flux
Extrapolated 3FGL Flux
Nightly-binned Flux points regardless of significance

Fermi-LAT
5-Day Bins
ULs for TS < 9

Swift-XRT: http://www.swift.psu.edu/monitoring/
Multiwavelength SED

Period 2 time-averaged spectral energy distribution

$E^2 \frac{dN}{dE} \text{ [MeV cm}^{-2} \text{s}^{-1}]$

ICRC 2017
Multiwavelength SED

Period 2 time-averaged spectral energy distribution

• **Intra-period variability** observed in X-ray spectrum.
• Shift in location of IC-energy Peak from 3FGL → Period 2:
  - $\Gamma_{3FGL} \ (2.12 \pm 0.03)$
  - $\Gamma_{Perio d\ 2} \ (1.96 \pm 0.16)$
• No significant evidence for curvature in Fermi-LAT spectrum → IC-peak shifted to higher energies.
• VERITAS spectrum suggests the peak is located < 100 GeV.
Conclusions and Future Work

- VERITAS has detected VHE emission spatially consistent with OJ 287 and temporally consistent with enhanced MWL activity from OJ 287.
- This strong (9.7 $\sigma$) detection allows for spectral and flux analysis of OJ 287.
- Intense follow up campaign initiated by VERITAS with many observations taken simultaneously with Swift-XRT.
- Clear X-ray variability observed during the VERITAS observations.
- Apparent shifting of the IC-energy peak from the 3FGL spectrum to higher energies during the VERITAS observations.
- Analysis still ongoing.
- Other multiwavelength data needs to be analysed (Swift-UVOT under analysis)
- Full Poissonian-Likelihood analysis required for further discussion of flux correlations across the different energy bands. Will be presented in a future publication.
- Full modelling of OJ 287’s broadband spectrum will be the subject of a future publication.
References

• S. Archambault et al., Upper Limits from Five Years of Blazar Observations with the VERITAS Cherenkov Telescopes, AJ, 151, 142 (2016).
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• CITE using a BBH model accurately predicted 2007 and 2015 optical outburst.
• Optical outburst expected in 2019!
Multiwavelength Light Curves

- Low statistics VERITAS data requires correct statistical handling of this data.
- Full Poison-Likelihood analysis of the flux and its correlation to different wavelengths will be presented in a future work.

[Graph showing multiwavelength light curves with green and red markers for VERITAS and Swift, respectively.]
VERITAS Results

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