Exceptionally bright TeV flares from LS I +61° 303

Anna O’Faoláin de Bhróithe for the VERITAS Collaboration
Brief intro to LS I +61° 303

- TeV-emitting high-mass X-ray binary system
- Contains a B0 Ve star and a compact object
- Nature of the compact object is unclear
- Orbital parameters [Aragona et al., 2009]:
  - $P \approx 26.5$ days
  - $e = 0.537 \pm 0.034$
  - $10^\circ < i < 60^\circ$
The multiwavelength emission pattern

- Periodic emission observed across the EM spectrum

![Diagram showing multiwavelength emission pattern with points labeled 0.081, 0.275, 0.313, and 0.775.]
The multiwavelength emission pattern

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- Factor 10 increase in radio flux density

Variability of order $\sim 0.1$ mag in optical
Variability of factor 1.5 in X-ray
Variability of factor 2 in GeV TeV detections at phases 0.6 – 0.8 and once at 0 – 0.1
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- Variability of order ~ 0.1 mag in optical
- Variability of factor 1.5 in X-ray
- Variability of factor 2 in GeV
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“Long-term VERITAS monitoring of LS I +61° 303 in conjunction with X-ray and GeV observation campaigns”
Poster 3 GA, Tuesday 16:00, Mississippi Foyer
Recent VERITAS observations of LS I +61° 303

- Observed for \(\sim 25\) hours between 2014 October 16 and December 12
- Detected at 21\(\sigma\) above 300 GeV
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Peak flux of 1st flare on Oct 18 with largest flux ever detected from this source

Peak flux of 2nd flare on Nov 14 with flux similar to the previous highest level detected (VERITAS 2006/7)

Flux back to normal levels in the 3rd orbit observed

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Calculating the significance of nightly variability

- 1st and 2nd orbits inconsistent with constant flux at the 10 \( \sigma \) level
- Test the hypothesis that, given a pair of nightly separated flux \((F_1, F_2)\), \(F_2\) is significantly larger than \(F_1\) (or the opposite)
- Assuming source flux and errors are normally distributed, can construct the 2D Gaussian function [Aliu et al., 2013]

\[
G(x, y) = \frac{1}{2\pi\sigma_1\sigma_2} e \left( \frac{-(x-F_1)^2}{2\sigma_1^2} - \frac{(y-F_2)^2}{2\sigma_2^2} \right)
\]

- A constant flux from night to night is given by \(y = x\)
- The probability that \(F_2 > F_1\) (or the opposite) is obtained through

\[
\int_{-\infty}^{+\infty} dx \int_{x}^{+\infty} G(x, y) dy
\]

- \(\sim 3 \sigma\) post trials (6 pairs of consecutive nights)
Characterising the flare profile

[Graph showing the relationship between orbital phase (φ) and flux (E>300 GeV) with data points for different orbits (Oct 2014, Nov 2014, Dec 2014).]
Characterising the flare profile
Characterising the flare profile

- Try to fit flares with an exponential function
  \[
  F(t) = F_0 e^{\frac{|t-t_0|}{\Delta \tau}}
  \]
  where \(\Delta \tau\) is the rise time for \(t < t_0\) and the fall time for \(t > t_0\)
  - This is a poor description of the data → try a different functional form
  - Try to fit the flares with an “asymmetric Gaussian” [Abdo et al., 2010]
    \[
    F(t) = F_c + F_0 \left( e^{\frac{t_0-t}{T_{\text{rise}}}} + e^{\frac{t-t_0}{T_{\text{fall}}}} \right)^{-1}
    \]
  - 1st flare: not well characterized
  - 2nd flare: rise time \(0.7 \pm 0.1\) days and fall time \(0.8 \pm 0.1\) days

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Energy spectrum

- Differential energy spectrum extracted from all data (average), first flare, and second flare
- All well-fit by a power law

\[ \frac{dN}{dE} = N_0 \left( \frac{E}{1 \text{ TeV}} \right)^\Gamma \]

- Average spectrum compatible with previous average measurements
- Flare spectra have similar index but higher normalizations

<table>
<thead>
<tr>
<th>Norm [×10^{-12} \text{ cm}^{-2} \text{ s}^{-1} \text{ TeV}^{-1}]</th>
<th>Index</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average</td>
<td>1.7 ± 0.7 ± 0.9</td>
</tr>
<tr>
<td>Flare 1</td>
<td>8.6 ± 1.0 ± 4.3</td>
</tr>
<tr>
<td>Flare 2</td>
<td>4.8 ± 0.4 ± 2.4</td>
</tr>
</tbody>
</table>
Energy spectrum

\[ \frac{dN}{dE} \text{ [cm}^{-2} \text{s}^{-1} \text{ TeV}^{-1}] \]

- 2014 fit to all data
- 2014 all data
- 2014 fit to F1
- 2014 F1 data
- 2014 fit to F2
- 2014 F2 data

\[ \text{Energy [TeV]} \]
A brief overview of models

[Massi et al., 2004]
A brief overview of models

Figure: Microquasar jet
[Khangulyan et al., 2008]

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A brief overview of models

Figure: Microquasar jet [Khangulyan et al., 2008]

Figure: Radio map from pulsar binary scenario [Dubus, 2006]
Limits on source properties

- Don’t know exact conditions of particle acceleration, but can still place some limits
- Follow [Khangulyan et al., 2008] — a general IC scenario
Limits on source properties

- Temperature of Be star is 22 500 K $\rightarrow$ avg energy of stellar photons is $3kT \approx 6\,\text{eV}$
  - IC scattering in deep KN regime
- Highest-energy photons observed are $\sim 10\,\text{TeV}$ $\rightarrow$ implies $10\,\text{TeV}$ electrons

### Acceleration timescale

$$t_{\text{acc}} \approx 0.1 \frac{E}{1\,\text{TeV}} \left( \frac{B}{G} \right)^{-1} \eta \, \text{s}$$

### Synchrotron cooling timescale

$$t_{\text{sy}} \approx 400 \left( \frac{B}{G} \right)^{-2} \left( \frac{E}{1\,\text{TeV}} \right)^{-1} \, \text{s}$$

### KN cooling timescale

$$t_{\text{KN}} \approx 10^3 \left( \frac{d}{10^{13} \, \text{cm}} \right)^2 \left( \frac{E}{1\,\text{TeV}} \right)^{0.7} \, \text{s}$$

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The hard gamma-ray spectral index requires a hard underlying electron spectral index → can constrain $t_{\text{KN}} < t_{\text{sy}}$

$$B < 0.6 \left( \frac{d}{10^{13} \text{ cm}} \right)^{-1} \left( \frac{E}{1 \text{ TeV}} \right)^{-0.85} \text{ G}$$

As the cooling time is dominated by $t_{\text{KN}}$, we can also set $t_{\text{acc}} < t_{\text{KN}}$

$$B > 10^{-4} \left( \frac{d}{10^{13} \text{ cm}} \right)^{-2} \left( \frac{E}{1 \text{ TeV}} \right)^{0.3} \eta \text{ G}$$

Plugging in $E = 10 \text{ TeV}$ and the apastron distance of $9.57 \times 10^{12} \text{ cm}$ gives $B < 0.1 \text{ G}$ and $B > 2 \times 10^{-4} \eta \text{ G} \rightarrow \eta \lesssim 500$
Limits on source properties

\[ \tau_{\text{acc}} = 1 \text{ day} \]

\[ \eta = 20, 28, 38, 53, 72, 100, 138, 190, 263, 362, 500 \]
References


