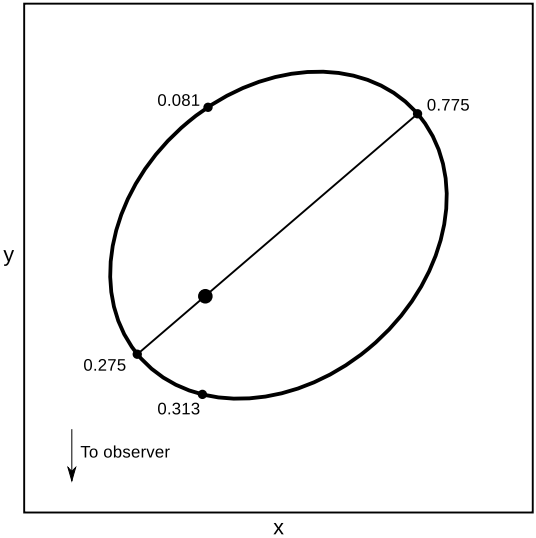
Exceptionally bright TeV flares from LS I +61° 303

Anna O'Faoláin de Bhróithe
for the VERITAS Collaboration

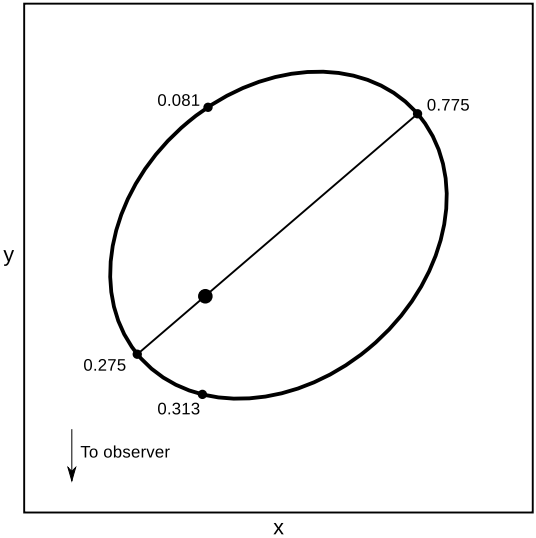
Brief intro to LS I +61° 303

- 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



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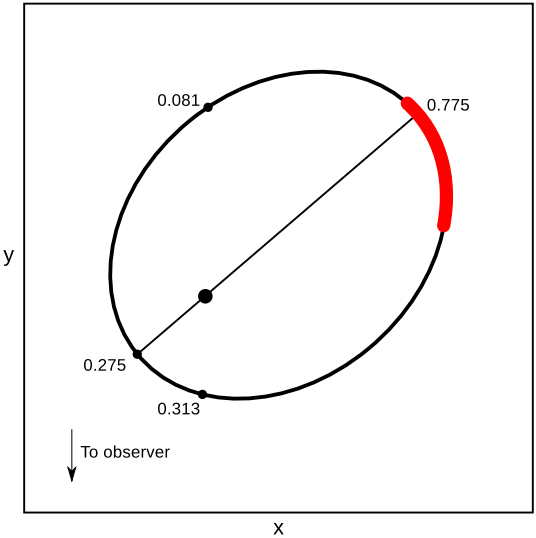

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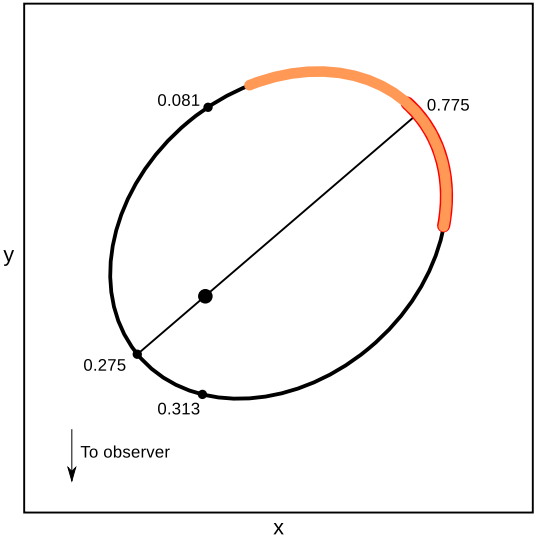

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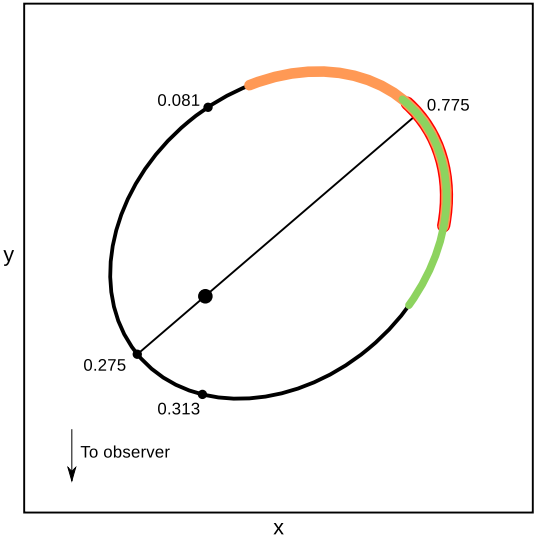

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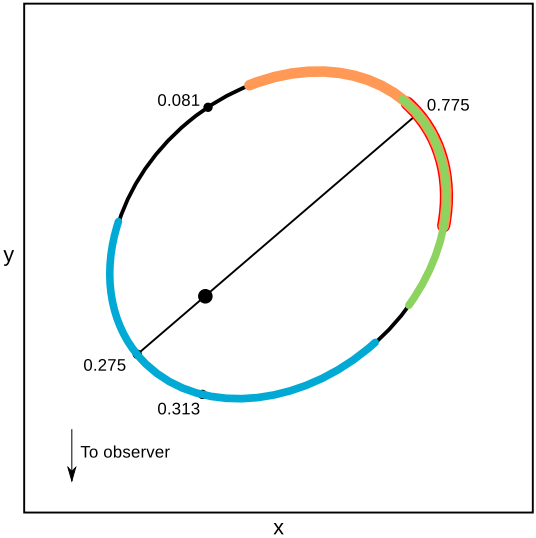

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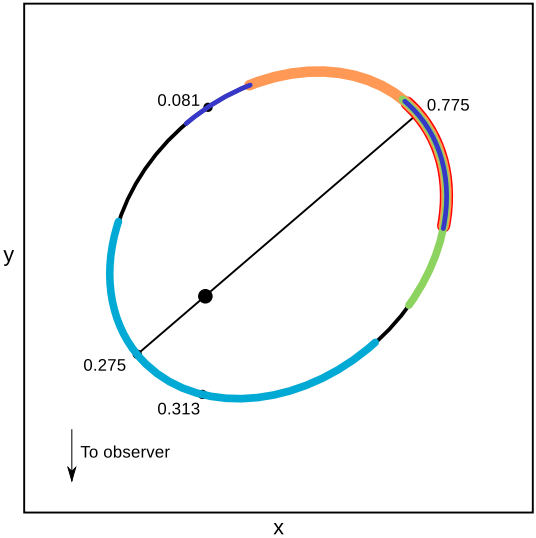

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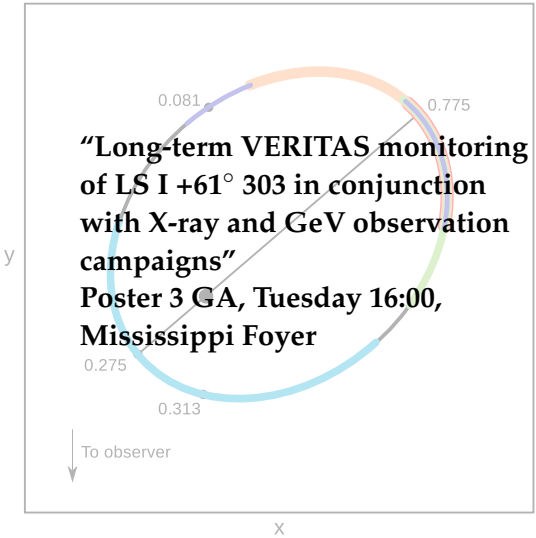
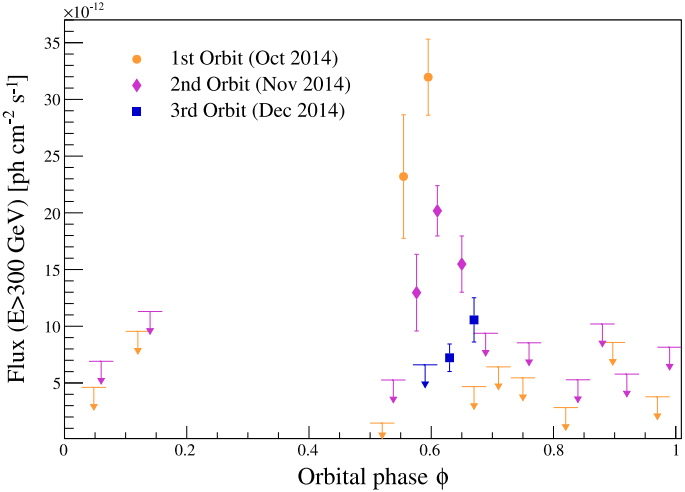


"Long-term VERITAS monitoring of LS I +61° 303 in conjunction with X-ray and GeV observation campaigns"
Poster 3 GA, Tuesday 16:00, Mississippi Foyer

Recent VERITAS observations of LS I +61° 303

- Observed for ~ 25 hours between 2014 October 16 and December 12
- Detected at 21σ above 300 GeV



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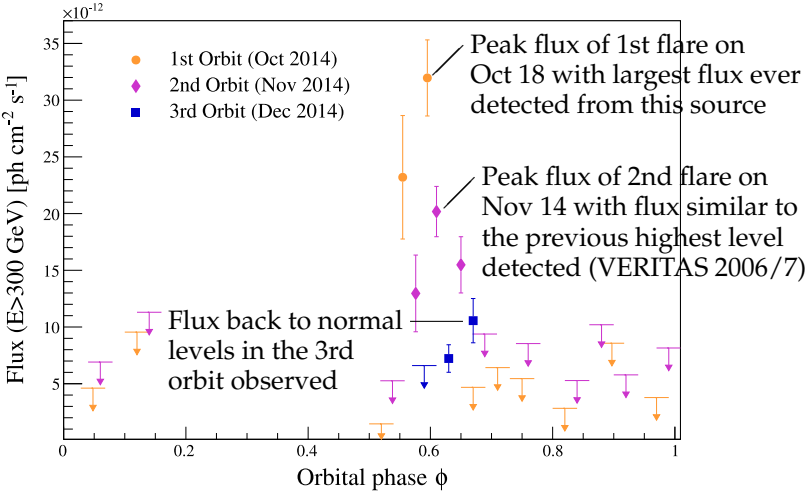


Calculating the significance of nightly variability

- 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]

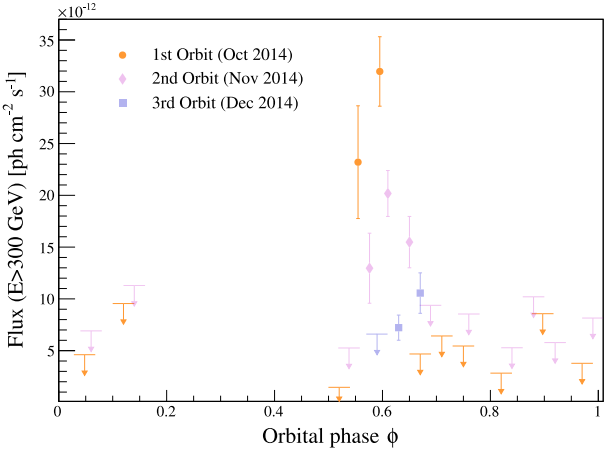
$$G(x,y) = \frac{1}{2\pi\sigma_1\sigma_2} e^{\left(\frac{-(x-F_1)^2}{2\sigma_1^2} - \frac{(y-F_2)^2}{2\sigma_2^2}\right)}$$

- 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



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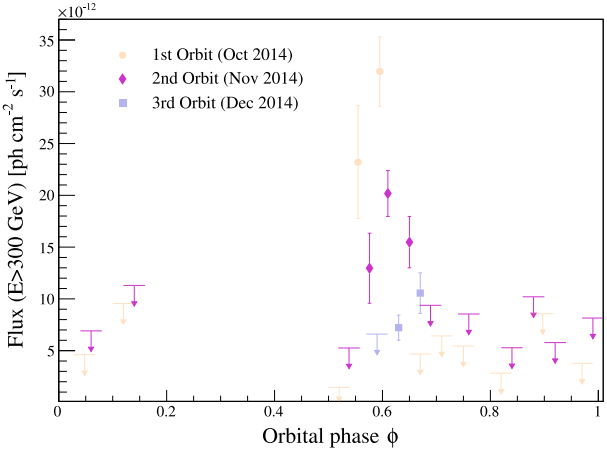


Characterising the flare profile

- 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 $\rightarrow$ try a different functional form
- Try to fit the flares with an "asymmetric Gaussian" [Abdo et al., 2010]

$$F(t) = F_c + F_0 \left(e^{\frac{t_0 - t}{T_{\rm rise}}} + e^{\frac{t-t_0}{T_{\rm fall}}} \right)^{-1}$$

- 1st flare: not well characterized
- 2nd flare: rise time 0.7 ± 0.1 days and fall time 0.8 ± 0.1 days

Energy spectrum

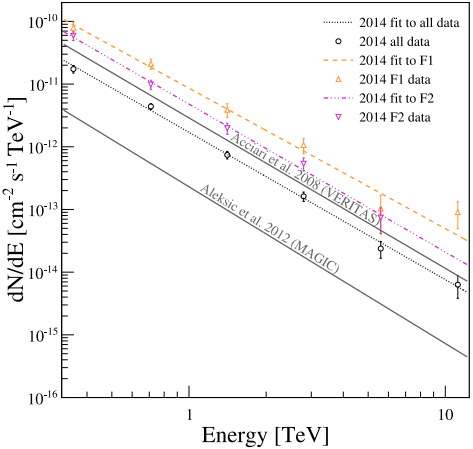
- Differential energy spectrum extracted from all data (average), first flare, and second flare
- All well-fit by a power law

$$\frac{dN}{dE} = N_0 \left(\frac{E}{1\,\mathrm{TeV}} \right)^{\Gamma}$$

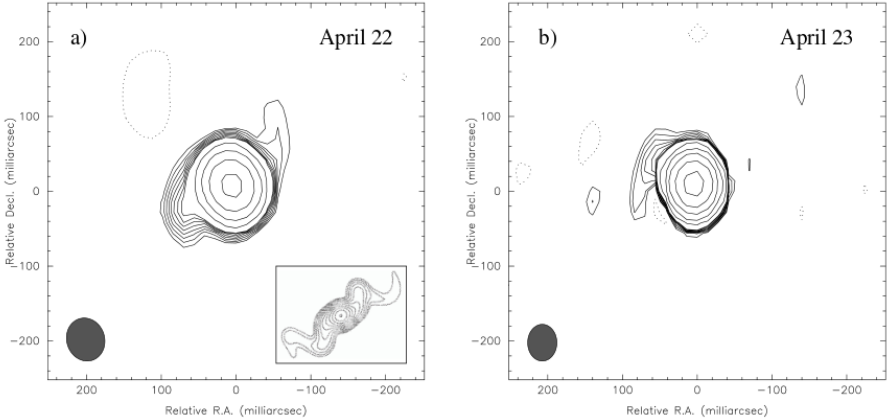
- Average spectrum compatible with previous average measurements
- Flare spectra have similar index but higher normalizations

	Norm $[\times 10^{-12}\ \mathbf{cm}^{-2}\ \mathbf{s}^{-1}\ \mathbf{TeV}^{-1}]$	**Index**
Average	$1.7 \pm 0.7 \pm 0.9$	$-2.35 \pm 0.32 \pm 0.3$
Flare 1	$8.6 \pm 1.0 \pm 4.3$	$-2.24 \pm 0.12 \pm 0.3$
Flare 2	$4.8 \pm 0.4 \pm 2.4$	$-2.36 \pm 0.12 \pm 0.3$

Energy spectrum



A brief overview of models



[Massi et al., 2004]

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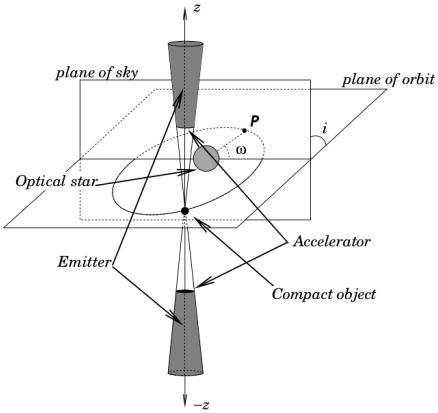

Figure: Microquasar jet
[Khangulyan et al., 2008]

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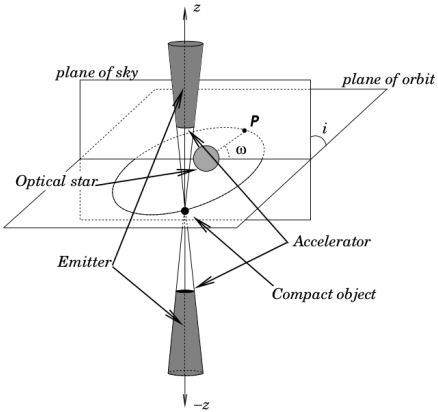


Figure: Microquasar jet [Khangulyan et al., 2008]

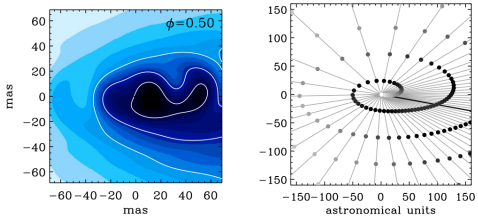
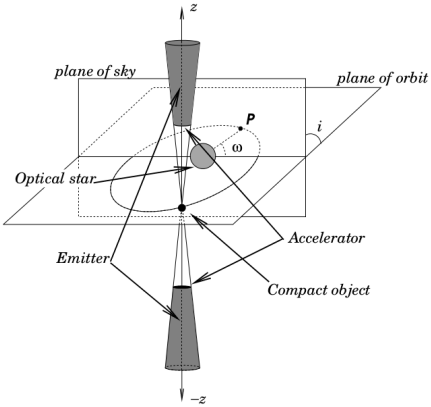


Figure: Radio map from pulsar binary scenario [Dubus, 2006]

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 $3kT \approx 6\,\mathrm{eV}$
  - IC scattering in deep KN regime
- Highest-energy photons observed are $\sim 10\,\mathrm{TeV} \rightarrow$ implies 10 TeV electrons

Acceleration timescale

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

Synchrotron cooling timescale

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

KN cooling timescale

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

Limits on source properties

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

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

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

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

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

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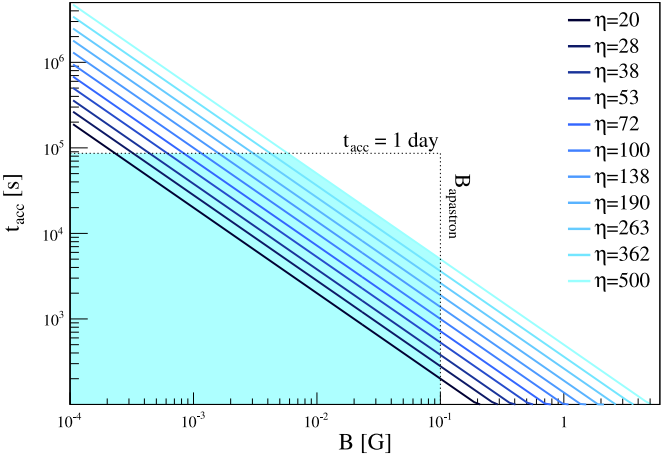

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