CTA 102 – year over year receiving you

Michael Zacharias,
M. Böttcher, F. Jankowsky, J.-P. Lenain, S. Wagner,
A. Wierzcholska

Theoretische Physik IV, Ruhr-Universität Bochum, Germany
Centre for Space Research, North-West University Potchefstroom, South Africa

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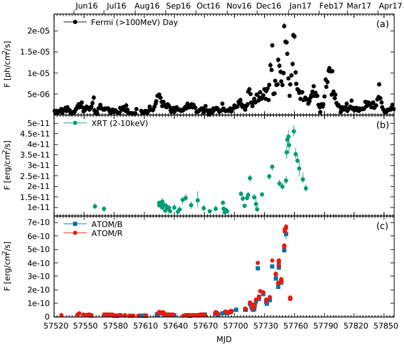
CTA 102



Daily fluxes of CTA 102 in 2016 and 2017 observed with (a) Fermi-LAT, (b) Swift-XRT, and (c) ATOM.

- CTA 102 is an FSRQ at $z = 1.037$
- Late 2016 till early 2017:
  - A roughly 4 months long flare at γ-ray, X-ray, and optical energies
  - Fluxes rose and fell steadily and symmetrically with short spikes on top
  - Optical flux rose a factor ~ 100
  - HE flux rose a factor ~ 50
  - A fast moving knot ($\delta \sim 35$) interacted with a standing feature
- What can cause such a flare?
- Where did the knot come from?

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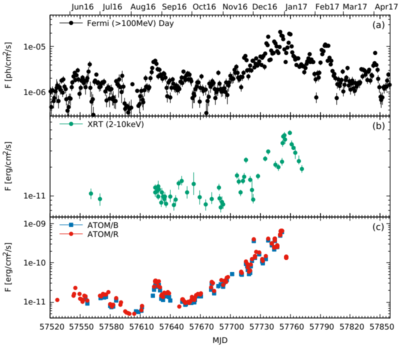

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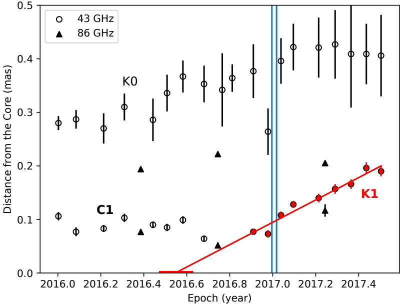

Distance of VLBI components from the core (Casadio+19).

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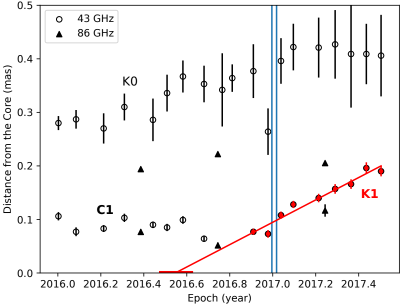

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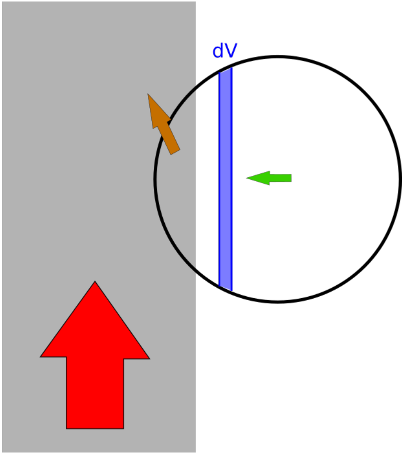
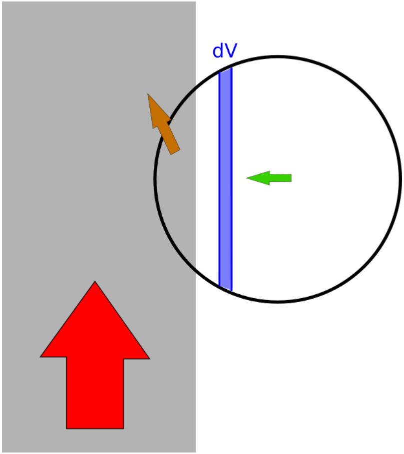
Ablation of a gas cloud



Ablation of a gas cloud by the relativistic jet.

- A gas cloud (black circle) enters the jet (gray area)
- The jet's ram pressure (red arrow) ablates the cloud's material that has already entered (orange arrow)
- The volume dV ablated in a time interval dt changes over time
- The number dN of ablated particles during dt changes over time

Ablation of a gas cloud



Ablation of a gas cloud by the relativistic jet.

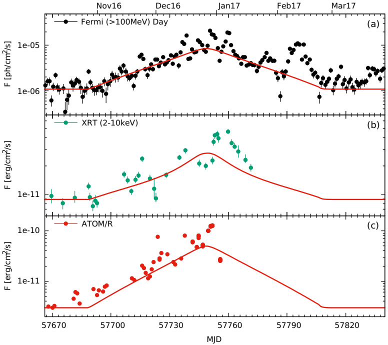
- Integration of ρ over $\mathrm{d}V$ gives $\mathrm{d}N$
- At any given time t since first contact, the injection term becomes

$$Q_{\mathrm{inj}} \propto \ln\left(\frac{t_0^2 + t_c^2}{t_0^2 + (t_c - t)^2}\right)$$

with

  - $t_c = \delta v_c R_c$
  - $t_0 = \delta v_c r_0$
  - δ: Doppler factor of the jet
  - v_c: Speed of the gas cloud
  - R_c: Radius of the gas cloud
  - $r_0 \propto (T_c n_0^{-1})^{1/2}$

Results



Model lightcurves (red) for (a) Fermi-LAT, (b) Swift-XRT, and (c) ATOM/R.

- The resulting lightcurves fit very well the long-term trend
- 1) Leptonic one-zone model
  - Only location: outer edge of the BLR
- 2) Hadronic one-zone model
  - Different locations possible
- Cloud parameters inferred from modeling

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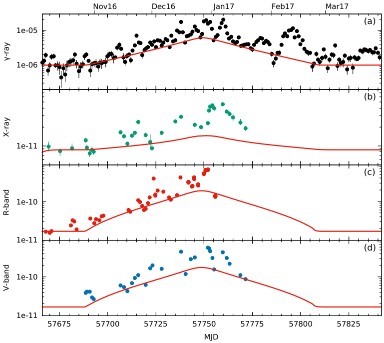

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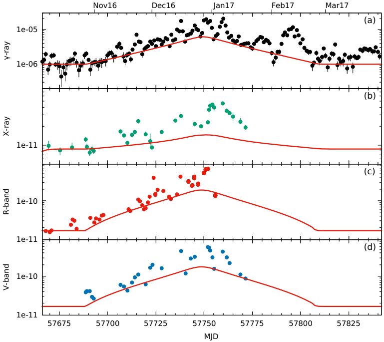

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Cloud parameters

- The radius depends on the duration of the event and the speed of the cloud
- Speed is determined as orbital speed around the SMBH

Model	Leptonic	Hadronic
Distance	6.5×10^{17} cm	1 pc
Speed	5.1×10^{8} cm/s	1.9×10^{8} cm/s
Radius	1.3×10^{15} cm	4.9×10^{14} cm
Density	2.5×10^{8} cm^{-3}	1.1×10^{7} cm^{-3}
Mass	3.9×10^{30} g	9.1×10^{27} g
Temperature	< 2.7 K	$\ll 2.7$ K

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- Inferred temperatures very low
  - Maybe not all particles are injected into the jet

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  - Star forming region
  - Atmosphere of a red giant star
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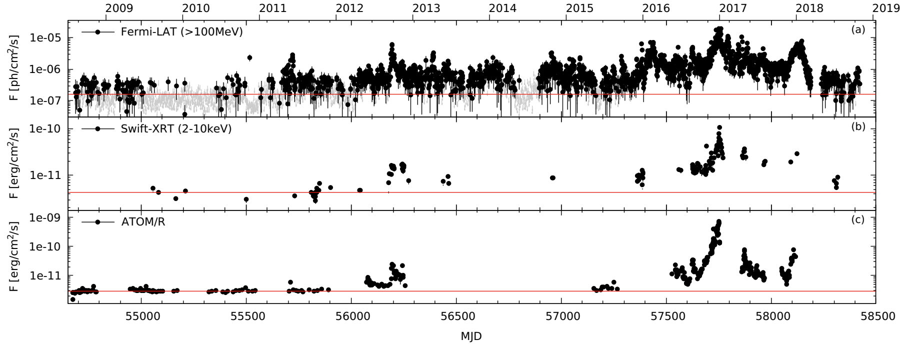
Monitoring of CTA 102



Monitoring lightcurves (10 years) with *Fermi*-LAT, *Swift*-XRT, and ATOM/R. Red lines give 2008-2012 averages. Note the logarithmic y-axis.

- Before 2012: very quiet
- 2012-2016: slight increase in average flux, variable
- 2016-2018: the average increased significantly, highly variable
- Something “symmetric” happened

Summary

- CTA 102 exhibited a ~ 4 months long, symmetrical flare
- A fast radio knot interacted with a recollimation shock
- **Ablation of a gas cloud** could be the cause of this flare/knot
- The models successfully fit the long-term trend
- “Cloud” could be a red giant star or part of a star forming region
- This scenario might also explain the 2-year symmetry in the total lightcurve

Paper 1: MZ et al., 2017, ApJ, 851, 72
Paper 2: MZ et al., 2019, ApJ, 871, 19

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Thank you for your attention!

Backup

Leptonic model: Spectrum and parameters

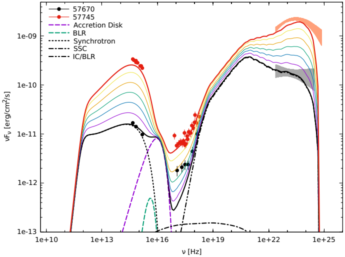

Figure 1: Spectra for a few time steps (data: MJD 57670 (black) and MJD 57745 (red)).

- Jet parameters:
  - BH distance: 6.5×10^{17} cm
  - Doppler factor: 35
  - Source radius: 2.5×10^{16} cm
  - Magnetic field: 3.7 G
  - Injection luminosity: 2.2×10^{43} erg/s
  - min. Lorentz factor: 13
  - max. Lorentz factor: 3000
  - e^- spectral index: 2.4
  - Escape time scaling: 10
  - Acceleration scaling: 1
  - BLR temperature: 5×10^4 K

  - Inj.lum. variation: 1.75×10^{43} erg/s
  - e^- spc.ind. variation: -0.6
- Observables:
  - Accretion disk: 3.8×10^{46} erg/s
  - BH mass: $8.5 \times 10^8\, M_\odot$
  - BLR luminosity: 4.14×10^{45} erg/s
  - BLR radius: 6.7×10^{17} cm

Leptonic model: Spectrum and parameters

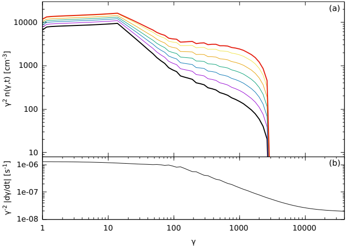

Figure 1: Particle distribution and cooling rate.

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Hadronic model: Spectrum and parameters

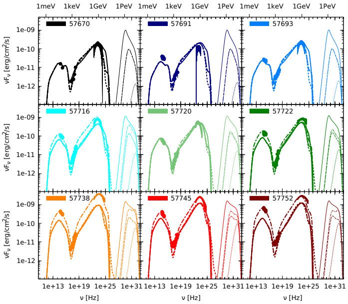

Figure 2: Spectra for a few time steps.

- Jet parameters:
  - BH distance: 3.09×10^{18} cm
  - Doppler factor: 35
  - Source radius: 2.0×10^{16} cm
  - Magnetic field: 60 G
  - Injection luminosity p: 1.3×10^{44} erg/s
  - min. Lorentz factor p: 1.0×10^{6}
  - max. Lorentz factor p: 1.0×10^{9}
  - spectral index p: 2.4
  - Injection luminosity e: 3.2×10^{41} erg/s
  - min. Lorentz factor e: 200
  - max. Lorentz factor e: 3000
  - spectral index e: 2.8
  - Escape time scaling: 5
  - Acceleration scaling: 30

  - Inj.lum. variation p: 5.0×10^{43} erg/s
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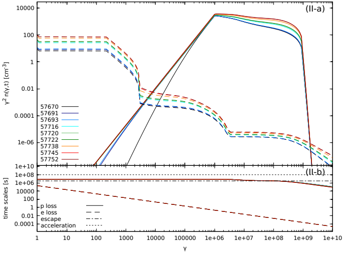

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Ablation of a gas cloud

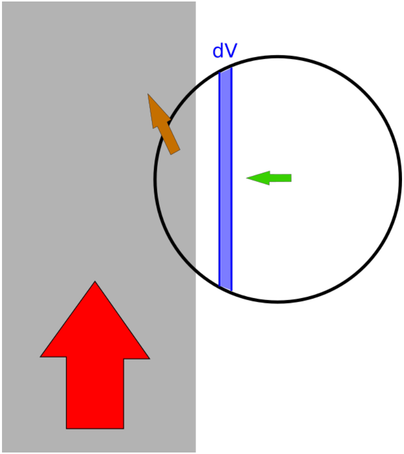

Figure 3: Ablation of a gas cloud by the relativistic jet.

- Calculation of dN requires the density profile ρ of the gas cloud
- Assuming an isothermal gas cloud held by its own gravity:

$$\rho \sim \left(1 + \frac{r}{r_0}\right)^{-2}$$

with $r_0 \propto (T_c n_0^{-1})^{1/2}$
  - T_c: Temperature of the gas cloud
  - n_0: Central density of the gas cloud

Cloud structure

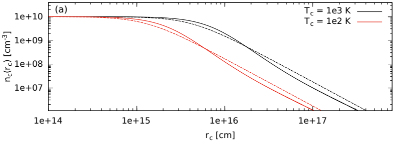

Figure 4: Density profile of an isothermal cloud (numerical = solid; approximation = dashed).

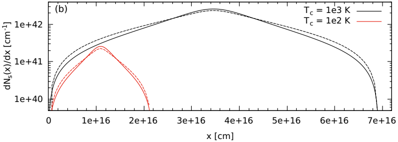

Figure 5: Particle number per slice of an isothermal cloud (numerical = solid; approximation = dashed).

- Isothermal, self-gravitating cloud:

$$\tau \frac{\mathrm{d}}{\mathrm{d}r}\left(\frac{r^2}{\rho}\frac{\mathrm{d}\rho}{\mathrm{d}r}\right) = -\rho r^2$$

  - r: radius
  - ρ: density
  - $\tau = k_B T_c/(4\pi m_p G)$
- Approximate solution:

$$\rho(r) = \frac{\rho_0}{\left(1 + \frac{r}{r_0}\right)^2}$$

  - $r_0 = \sqrt{3\tau/\rho_0}$
  - ρ_0: central density
- Integration over slice volume gives particle number per slice

Ram pressure vs gravity

- Ram pressure of the jet can overcome the gravitational pressure that confines the cloud
- Minimum density of the jet to ablate a gas cloud (assuming no relativistic protons):

$$
\begin{aligned}
n_{j,e,\mathrm{min}} \quad &\gtrsim \quad 2.8 \times 10^{-12} \left(\frac{a}{0.1}\right)^{-1} \left(\frac{\Gamma_j}{10}\right)^{-1} \left(\frac{\Gamma_j - 1}{9}\right)^{-1} \\
&\times \left(\frac{M_c}{0.01\,M_\odot}\right) \left(\frac{R_c}{10^{15}\,\mathrm{cm}}\right)^{-2} \ \mathrm{cm}^{-3}
\end{aligned}
$$

- Thermal pressure of the cloud (and maybe magnetic field pressure) are neglected
- Even a solar-like star might be stripped of its outer envelope