

The long-lasting activity in the FSRQ CTA 102

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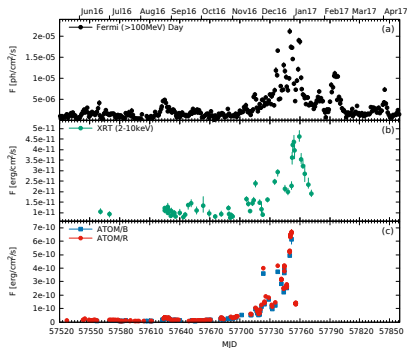


Figure 1: Daily fluxes of CTA 102 in 2016 and 2017 observed with (a) Fermi-LAT, (b) Swift-XRT, and (c) ATOM.

- 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
- What can cause such a flare?

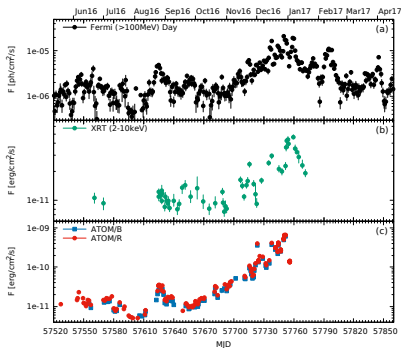


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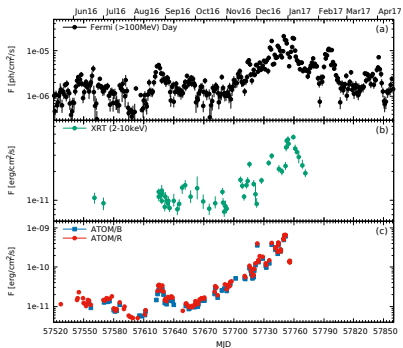


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Ablation of a gas cloud

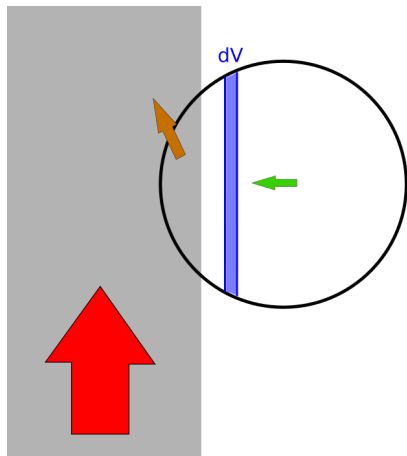


Figure 2: Ablation of a gas cloud by the relativistic jet.

- 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
- Integration of ρ over dV gives dN

Ablation of a gas cloud

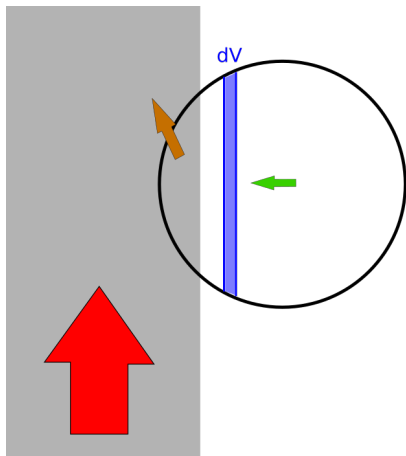


Figure 3: Ablation of a gas cloud by the relativistic jet.

- At any given time t since first contact, the injection term becomes

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

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
- $r_0 \propto (T_c n_0^{-1})^{1/2}$

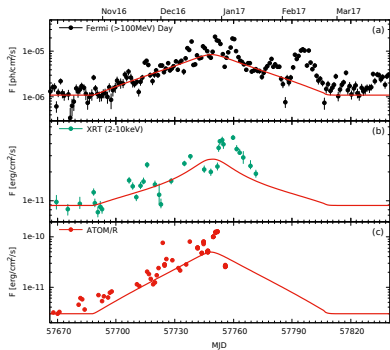


Figure 4: Model lightcurves (red) for (a) Fermi-LAT, (b) Swift-XRT, and (c) ATOM/R.

- 1) Leptonic one-zone model
 - Only location: outer edge of the BLR
- 2) Hadronic one-zone model
 - Different locations possible
- Both models reproduce the data reasonably well
- Cloud parameters inferred from modeling

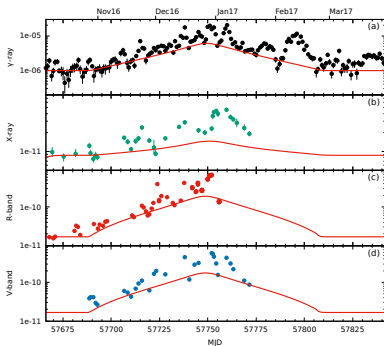


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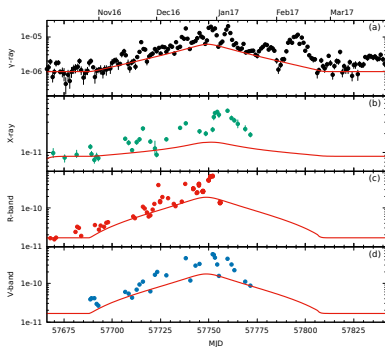


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Cloud parameters

- 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	≪ 2.7 K

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- Hadronic model requires less injected particles than leptonic model
- Inferred temperatures very low
 - Maybe not all particles are injected into the jet

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 - BLR (unlikely)
 - Star forming region
 - Atmosphere of a red giant star
- What is the very-long-term behavior?

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Monitoring of CTA 102

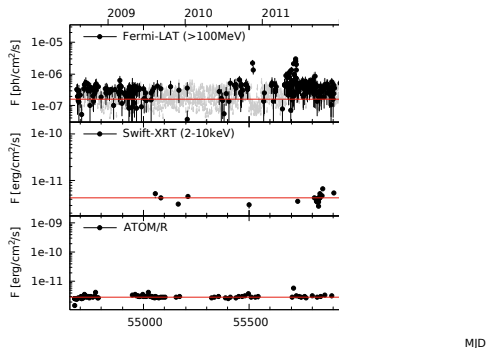


Figure 5: Monitoring lightcurves (10 years) with *Fermi*-LAT, *Swift*-XRT, and ATOM/R. Red lines give 2008-2012 averages. Note the logarithmic y-axis.

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

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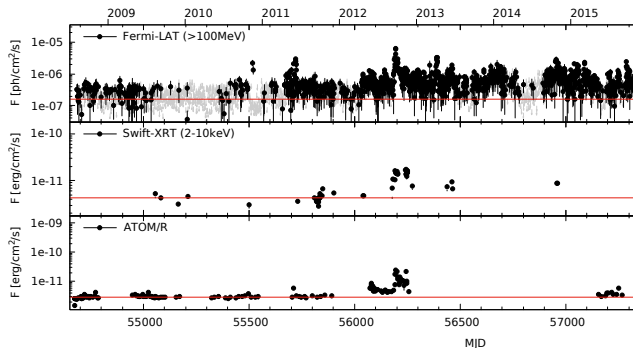


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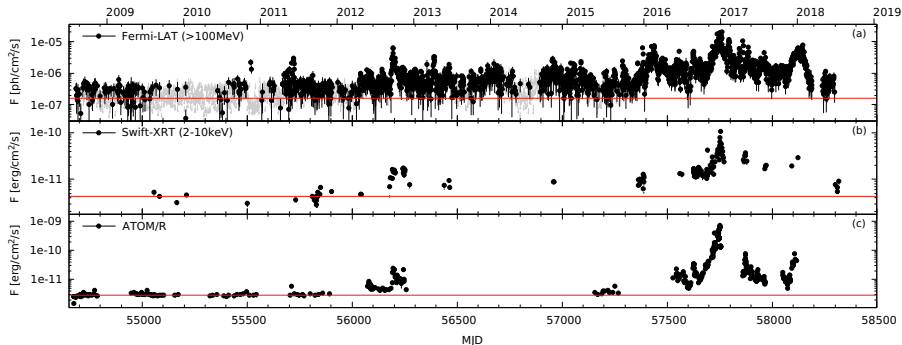


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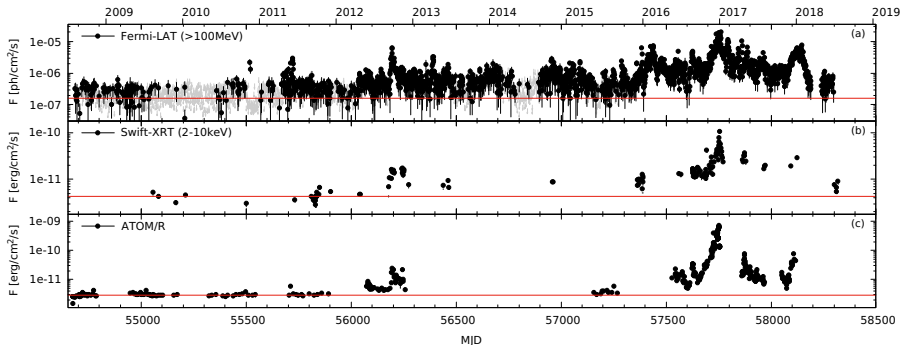


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- CTA 102 exhibited a ~ 4 months long, symmetrical flare
- **Ablation of a gas cloud** could be the cause of this flare
- Leptonic and hadronic models successfully fit the long-term trend
- “Cloud” could be a red giant star or part of a star forming region
- These scenarios might also explain the 2-year symmetry in the total lightcurve

Leptonic Model: MZ et al., 2017, ApJ, 851, 72

Hadronic Model: MZ et al., *submitted*

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Thank you for your attention!

Leptonic model: Spectrum and parameters

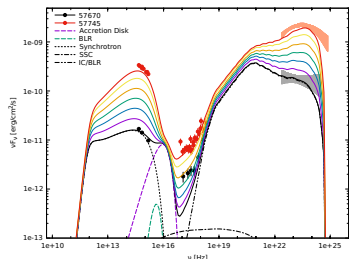


Figure 6: Spectra for a few time steps (data: MJD 57670 (black) and MJD 57745 (red)).

● 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

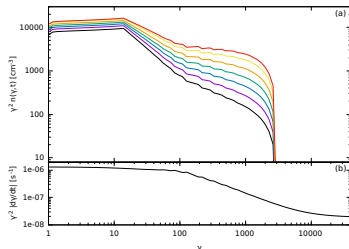


Figure 6: Particle distribution and cooling rate.

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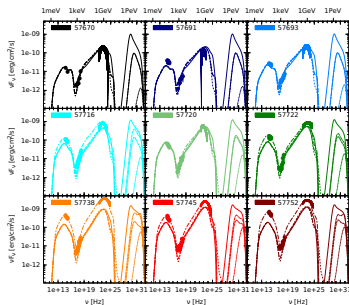


Figure 7: Spectra for a few time steps.

● 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
 - spc.ind. variation p: -0.3
 - Inj.lum. variation e: 8.0×10^{41} erg/s

Hadronic model: Spectrum and parameters

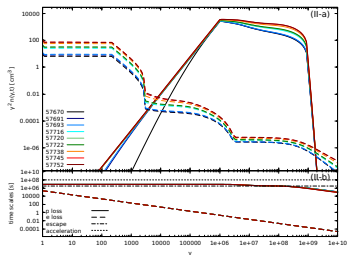


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Ablation of a gas cloud

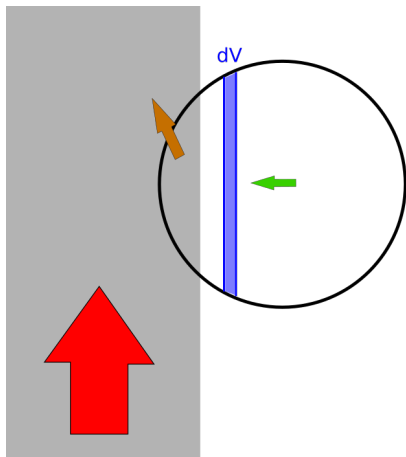


Figure 8: Ablation of a gas cloud by the relativistic jet.

- 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

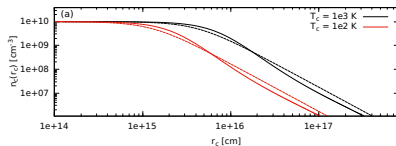


Figure 9: Density profile of an isothermal cloud (numerical = solid; approximation = dashed).

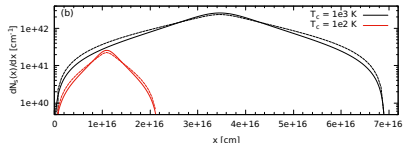


Figure 10: Particle number per slice of an isothermal cloud (numerical = solid; approximation = dashed).

- Isothermal, self-gravitating cloud:

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

- 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):

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

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