Star-Jet Interactions and Gamma-Ray Flares

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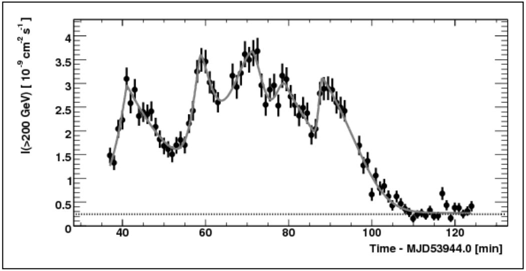
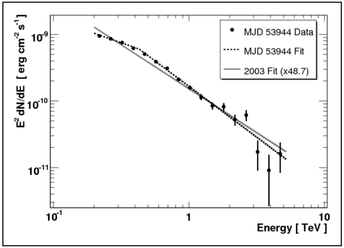
Outline

PKS 2155–304 observations





The observed parameters of the PKS 2155−304 flares (H.E.S.S. data)

$$L_\gamma \approx 10^{47} \text{erg s}^{-1}$$

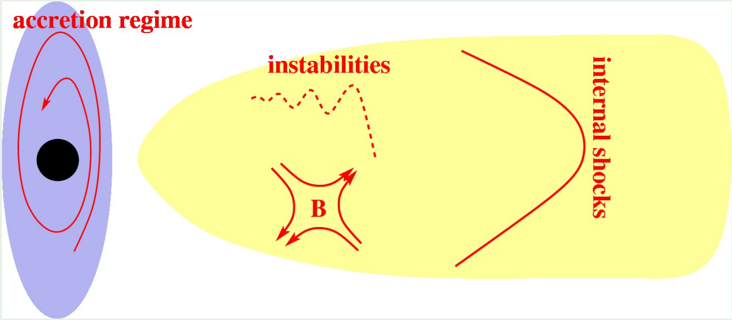
$$\tau \approx 200 \text{ s}$$

$$L_X \sim 10^{46} \text{erg s}^{-1}$$

(Aharonian et al 2007)

What are the Blobs in Powerful Jets?

There are a lot of hypothetical blobs



Internal Shocks, Magnetic Reconnection, Change in Accretion, Instabilities....

Blobs of external origin

- If blobs have external origin, they can be **very small** as compared to the hydrodynamical scale of the jet....
- External blobs contain **no energy** (as compared to the jet)
- I.e. external blobs must be able to **trigger an intensive interaction**. To be heavy?
- Compact and heavy, i.e **DENSE:** stars, BLR clouds?

Specific realization of such blob formation:

Jet-Red Giant Interaction Scenario

Main Ingredients

AGN jet

- Relativistic outflow ($\Gamma_{\rm bulk} \sim 10 - 100$, likely depends on the distance)
- Narrow: typically one adopts $\theta \simeq \Gamma^{-1}$, i.e.,
- Cross section:

$$\omega \simeq 10^{17} \Gamma_{1.5}^{-1} R_{\rm pc} {\rm cm}$$

Stars around BH

- Moves with Keplerian velocity:

$$V_* \simeq 600 M_{\rm BH}^{1/2} R_{\rm pc}^{-1/2} {\rm km/s}$$

- Density (quite uncertain): $\rho_* \simeq \rho_0 R^{-a}$

Mass injection between 10^{-2} and 10^{-1} pc:

$$\dot{M}_* \simeq 2 \times 10^{-5} \frac{\rho_0 M_{\rm BH,8}^{1/2}}{\Gamma_{1.5}} \int\limits_{0.01}^{0.1} x^{1/2-a} dx \; [{\rm pc}^3 \, {\rm yr}^{-1}] \,,$$

Probability to get a star to a jet

Murphy et al. 1991

- it was revealed that "a" spans a quite broad range depending on the mass accumulated in the central parsec
- It was obtained that $a = 7/2$ for $\bar{\rho} = 10^6 M_\odot \mathrm{pc}^{-3}$ and $a = 1/2$ for $\bar{\rho} = 10^8 M_\odot \mathrm{pc}^{-3}$

Mass injection appears to depend very weakly on a

$$\dot{M}_* \simeq 2 \times 10^2 M_{\mathrm{BH},8}^{1/2} M_\odot \Gamma_{1.5}^{-1} \mathrm{yr}^{-1}$$

for $10^{-2} < R_{\mathrm{pc}} < 0.1$

One can expect HUNDREDS of stars entering per year which can contain a few Red Giants or young stars per year...

RIKEN

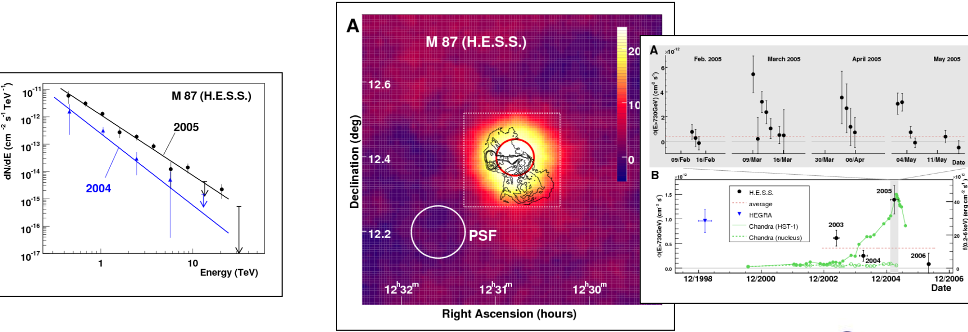
VHE variability in M87

H.E.S.S., MAGIC, VERITAS observations of M87

Several flashes were observed in 2006, 2008, 2010.

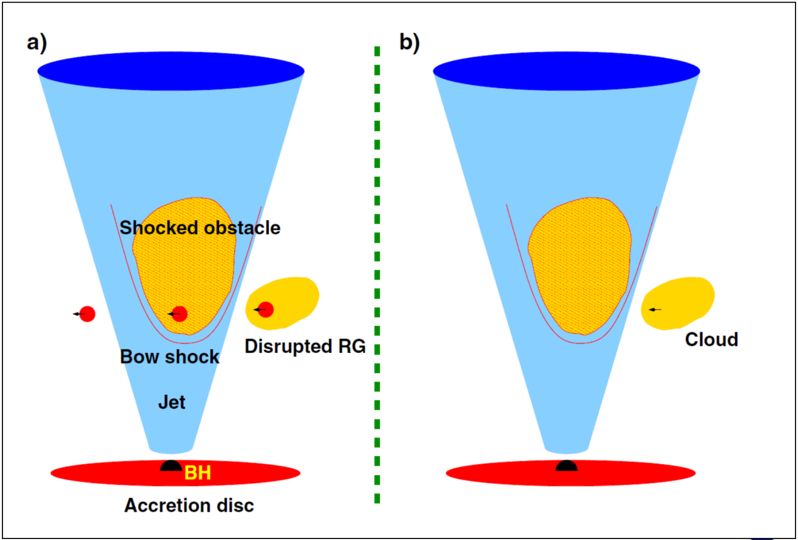
Variability on scales $t \sim 1$day

The flux $L_\gamma \sim 10^{42}$ergs s^{-1} $\qquad E_{\gamma,max} \simeq 20$TeV.



(Aharonian et al 2006; Abramowski et al. 2011; Aliu et al. 2011)

Cloud/Star — Jet interaction



(Barkov et al 2010, 2012b)

Star envelope evolution (Numerical results)

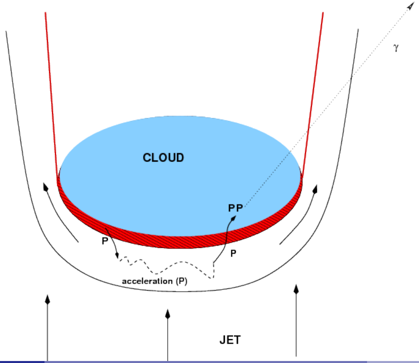
Uniform cloud

(Bosch-Ramon et al 2012)

p-p interaction

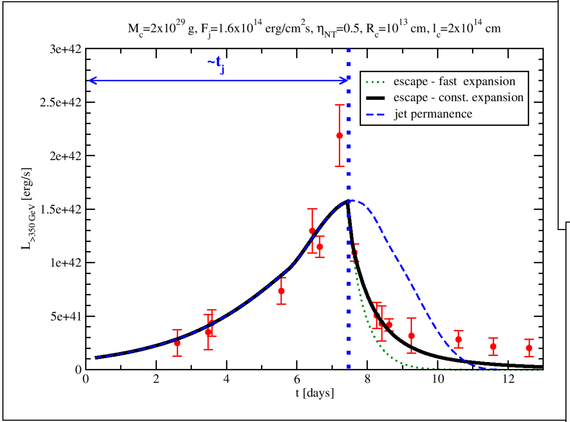
The cloud density can be very high making the *pp* interactions to be the most plausible mechanism for the gamma-ray production in the RG-jet interaction scenario: in this case the characteristic cooling time for *pp* collisions is

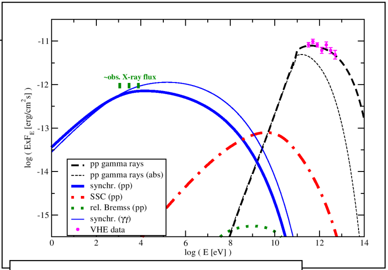
$$t_{pp} \approx \frac{10^{15}}{c_f n_c} = 10^5 \, n_{c,10}^{-1} c_f^{-1} \, \mathrm{s} \qquad \chi \equiv E_\gamma / E_p = 0.17 \, [2 - \exp(-t_v / t_{pp})]$$

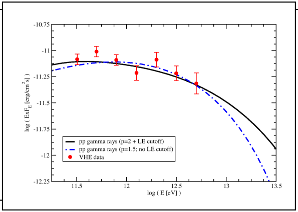


VHE light curves and spectra (Numerical model)

$\xi = 0.5$ and $Q_p(E) \propto E^{-2}$



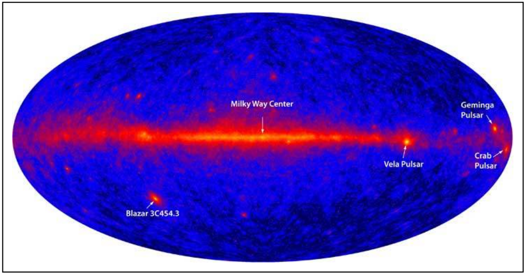


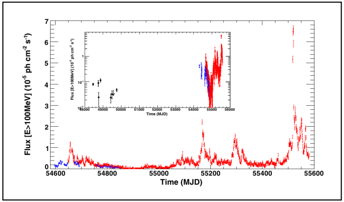


(Barkov et al 2012b)

Fast variability in GeV blazars (3C454.3)

3C454.3 observations





The observed parameters of the 3C454.3 flares (*Fermi* data)

$$L_\gamma \approx 2 \times 10^{50} \mathrm{erg\,s}^{-1}$$

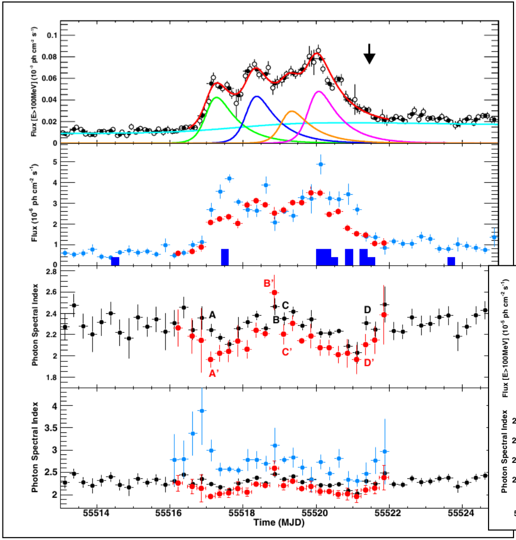
$$\tau_\mathrm{r} \approx 4.5\,\mathrm{h}$$

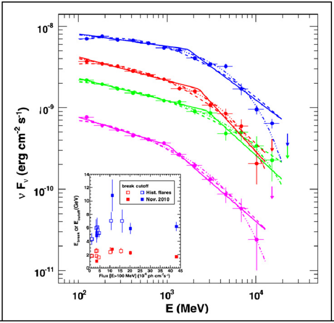
$$L_X \sim 5 \times 10^{47} \mathrm{erg\,s}^{-1}$$

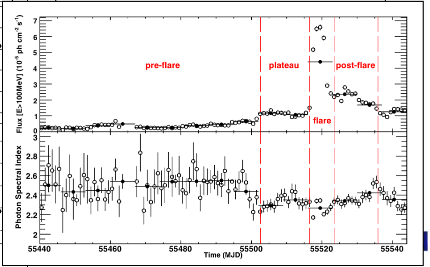
(Abdo et al. 2011; Vercellone et al. 2011)

3C454.3 observations (2010 November)

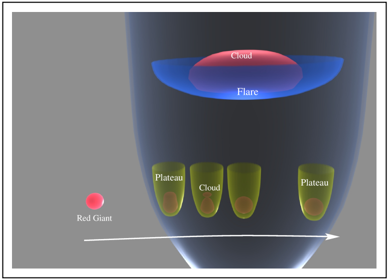
(Abdo et al 2011)







Sketch and Plateau model



$$\dot{M}_* \approx 10^{24} L_{\gamma,49} \xi_{-1}^{-1} \Gamma_{j,1.5}^{-3} \text{ g/s}.$$

The cosmic ray/X-ray excite stellar wind (Basko et al. 1973; Dorodnitsyn et al. 2008),

$$\dot{M} \approx 10^{24} \alpha_{-12} R_{*,2}^{5/2} M_{*,0}^{-1/2} \chi P_{0,6} \, \text{g s}^{-1}$$

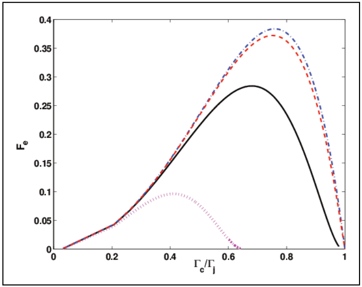
which providing limitations on the stellar radius

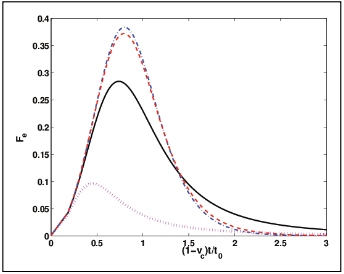
$$R_{*,2} \gtrsim \left(\frac{2\bar{F}_e M_{0,*}^{1/2}}{\alpha_{-12}\chi} \right)^{2/5} .$$

Relativistic Stage

At the relativistic stage, the dynamics of the cloud is described by the following equation:

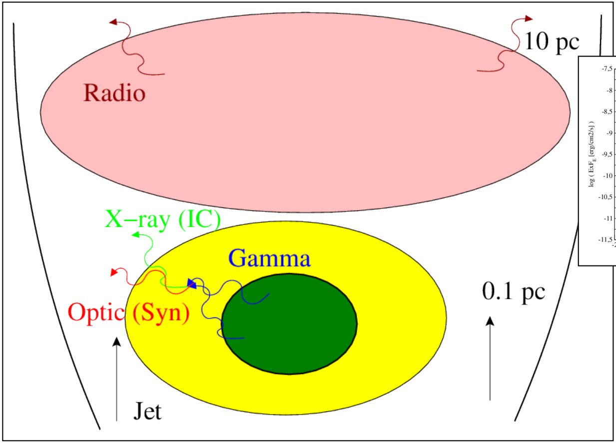
$$\frac{dg}{dy} = \left(\frac{1}{g^2} - g^2\right)\frac{D}{y^2}, \quad D \equiv \frac{L_{\rm j} r_{\rm c}^2}{4\theta^2 \Gamma_{\rm j}^3 z_0 c^3 M_{\rm c}}, \quad g \equiv \frac{\Gamma_c}{\Gamma_j}, \quad y \equiv \frac{z}{z_0}.$$

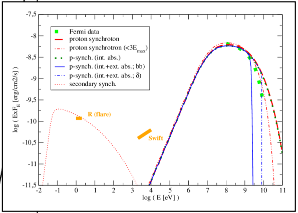




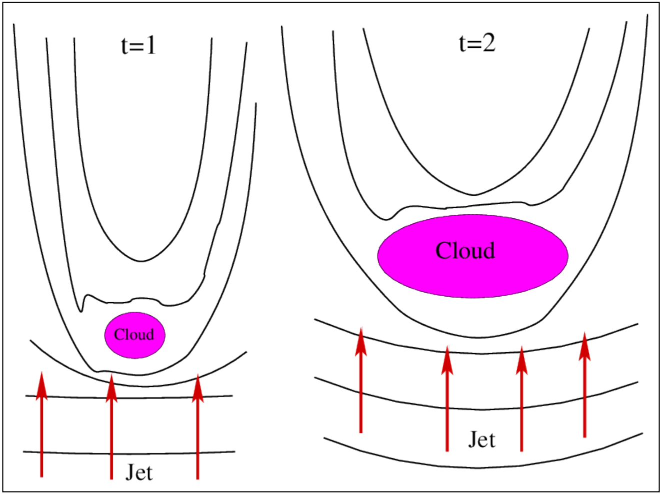
Solutions of the equation shown as $F_e \equiv L/L_{max}$ vs Lorentz factor of the cloud and as L/L_{max} vs the observed time ($t_0 = z_0/D\delta\Gamma_j c$). $D = 100$, 10, 1 and 0.1. (Barkov et al 2012a)

Radiation Model: Geometry





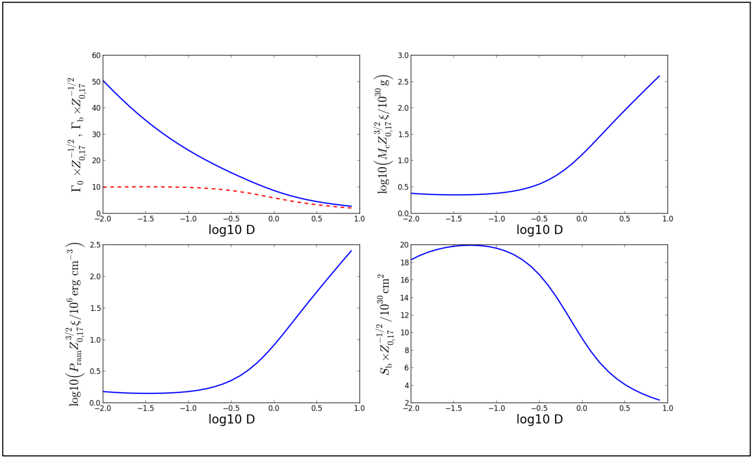
The magnetic field shielding



In the framework of JRGI scenario the magnetic field shielding allows to magnetic field remain low inside the blob (Barkov et al. 2012b).

$B_c \ll B_j$

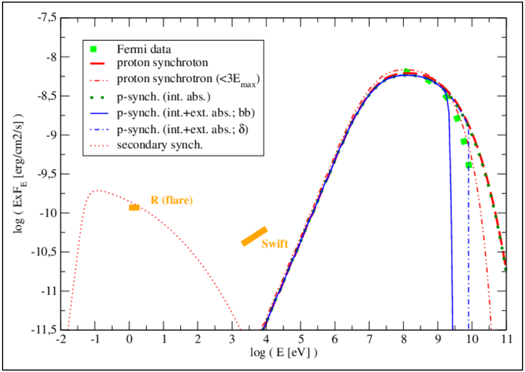
The Model Solution for the Main Flare

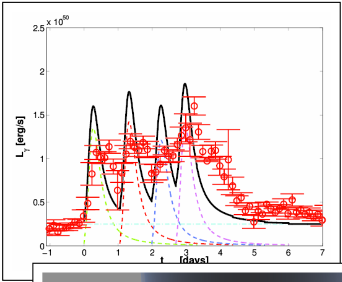


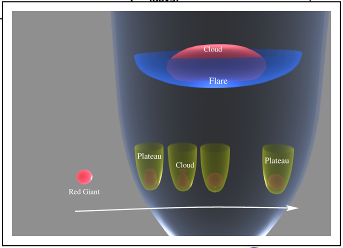
$$D \equiv \frac{L_j r_c^2}{4\theta^2 \Gamma_j^3 z_0 c^3 M_c} \qquad L_j \geq 10^{48} \quad \mathrm{erg\ s^{-1}}$$

$$M_{BH} \approx 10^9 M_\odot \qquad \delta_b \approx 20$$

Dynamical light curve + Radiation spectra: Proton synchrotron and secondary synchrotron

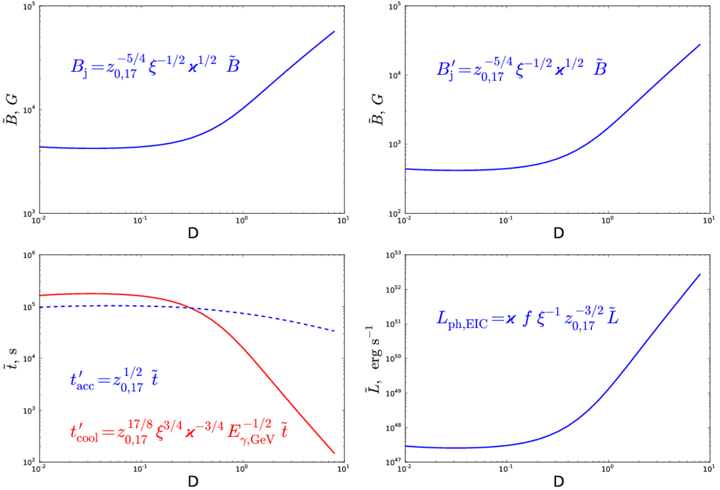




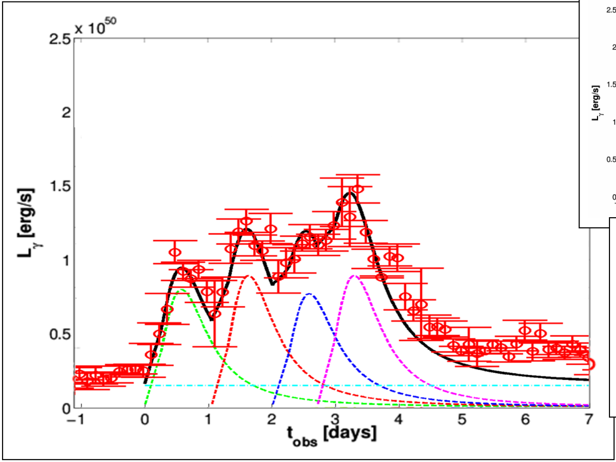


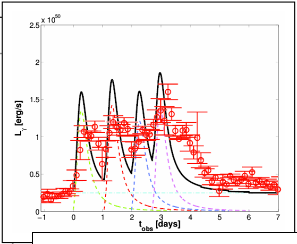
$$t_{\mathrm{acc}}/(2\Gamma_b^2) \approx 5\ \mathrm{h}.$$

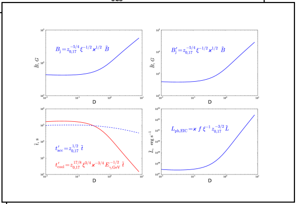
Radiation Model: limitations



Radiation Model: Dynamical light curve + cooling time

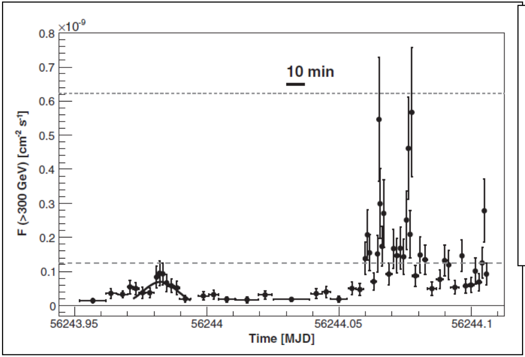


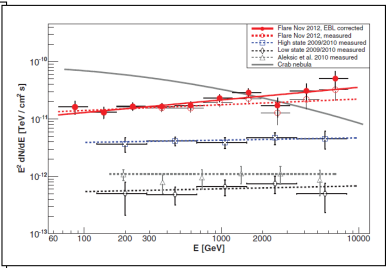




A few comments about IC310

TeV Flare in IC310





The observed parameters of the IC310 TeV flares (MAGIC data)

$$L_\gamma \approx 2 \times 10^{44} \mathrm{erg\ s}^{-1}$$

$$\tau_\mathrm{r} \approx 4.8\ \mathrm{min}$$

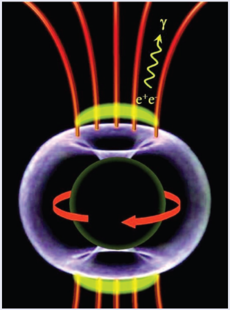
Aleksic et al (2014)

Black Hole Magnetospheric Model:

Optimistic Total Energetic Budget

- $\Delta V \lesssim h B_{\rm bh} \frac{R\Omega_{\rm F} \sin\theta}{c}, \quad \frac{\Omega_{\rm F}}{c} \simeq \frac{1}{4 r_g}$
- $L_{\gamma,ms} < 4\pi R^2 c \kappa \rho_{\rm GJ} \Delta V, \quad \rho_{\rm GJ} = \Omega_{\rm F} B_{\rm bh} \sin\theta / (2\pi c)$
- $L_{\gamma,ms} < \frac{1}{8} \kappa B_{\rm bh}^2 r_{\rm g} h c \sin^2\theta$ (2x larger compare to Balandford-Znajek)
- $\dot{m} < 4 \times 10^{-3} \eta \alpha_{ss} \beta_m^{1/7} M_8^{-1/7}$ the maximum accretion rate compatible with vacuum gap (similar to Levinson&Rieger 2011)
- $B_{\rm d} = \sqrt{8\pi\beta_{\rm m} p_g}, \quad h = 10^{13} t_{\rm var,5}\,{\rm cm}$
- $L_{\gamma,ms} < 10^{43} \beta_{\rm m} \kappa t_{var,5} M_{\rm BH,8}^{-1/7} \sin^2\theta$ erg s^{-1}
- $L_{\gamma,\rm observed} \approx 2 \times 10^{44}$ erg s^{-1}

Black Hole magnetospher



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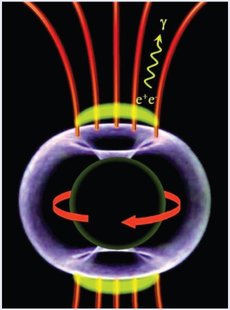

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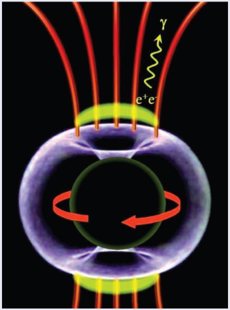
Black Hole magnetospher



Aleksic et al (2014)

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- $L_{\gamma,\rm observed} \approx 2 \times 10^{44} {\rm erg\, s^{-1}}$
- $L_{\gamma,\rm observed} \gg L_{\gamma,ms}$

Black Hole magnetospher

Aleksic et al (2014)

Conclusions

- In the case of 3C454.3 the radiation in the GeV energy range can be effectively produced through proton synchrotron radiation, Jitter or EIC in the Thompson regime.
- The process can render suitable conditions for energy dissipation and proton acceleration, which could explain the detected day-scale TeV flares in 2010 from M87 via proton-proton collisions.
- In IC310 magnetospheric model do not work.

Based on:

- MVB, F.A. Aharonian and V. Bosch-Ramon, (M87); ApJ (2010) 724, 1517
- MVB, F.A. Aharonian, S.V. Bogovalov, S.R. Kelner and D.V. Khangulyan, (PKS 2155−304); ApJ (2012) 749, 119
- V. Bosch-Ramon, M. Perucho and MVB, (M87); A&A (2012) 539, 69
- MVB, V. Bosch-Ramon and F.A. Aharonian, (M87); ApJ (2012) 755, 170
- D.V. Khangulyan, MVB, V. Bosch-Ramon, F.A. Aharonian and A. Dorodnitsyn, (3C454.3) ApJ (2013) 774, 113

Thank you!!!

Time variability

The shape of the function F_e can be treated as a time profile of the particle acceleration rate providing us with its the characteristic timescale. In the extreme case, when the blob eclipses the entire jet (i.e. $\omega^2/r_{\rm c}^2 \sim 1$), this scale depends only on the jet Lorentz factor Γ_j and power L_j, as well as on the mass of the cloud M_c:

$$\Delta t \approx 200\Gamma_{j,1} L_{\rm j,45}^{-1} M_{\rm c,25}\,{\rm s}$$