Rapid TeV and GeV Variability in AGNs as Result of Jet-Star Interaction

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Ginzburg Conference of Physics
29 May 2012

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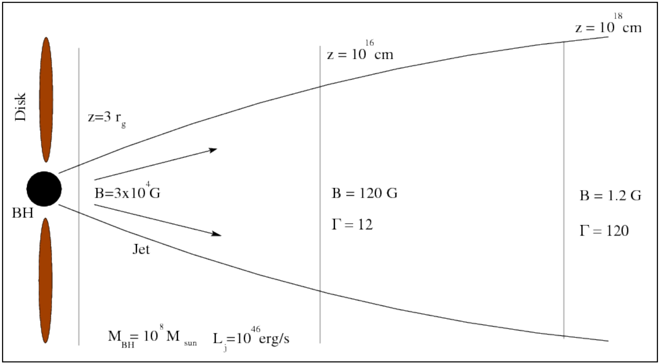
Outline

1. Structure of the Magnetically driven jet
2. VHE ultra short variability
3. VHE variability in M87
4. Very fast variability in TeV blazars (PKS 2155$-$304)
5. Very fast variability in GeV blazars (3C454.3)
6. Conclusions

Structure of the Magnetically driven Jet

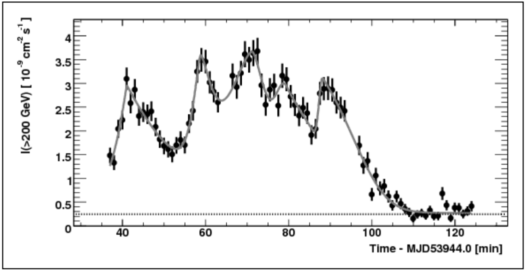
Sketch of the jet with characteristic magnetic field strengths and bulk Lorentz factors at typical distances from a BH with mass $M_{BH} = 10^8 M_\odot$ and $L_j = 10^{46}$ erg s^{-1}.

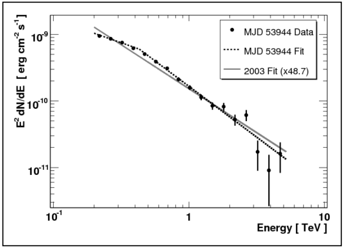


$$\Gamma_j = \frac{\omega}{4 r_g}, \qquad \theta \sim \frac{1}{\Gamma_j}, \qquad B_c \approx \frac{2}{z}\left(\frac{L_j}{c}\right)^{1/2} G$$

(Komissarov et.al.,2007 & 2009; Beskin et.al., 2006)

PKS 2155–304 observations





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

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

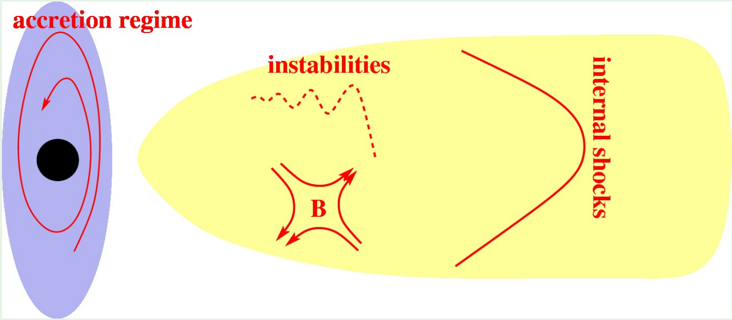
$$\tau \approx 200 \text{ s}$$

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

(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....

Fundamental Requirements on the blob properties

BLOBS MUST BE SMALL AND CONTAIN A LOT OF ENERGY (OR BE ABLE TO TRIGGER POWERFUL INTERACTION)

instabilities

can be very small

no energy

accretion

hydrodynamical scale

a lot of energy

shocks

very intensive interaction

at hydrodynamical scale

reconnection

a lot of energy

hydrodynamical scale

Blobs of external origin

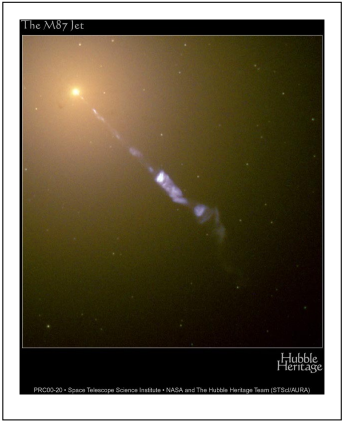
- If blobs have external origin, they can be **very small** as compared to the hydrodynamical scale of the jet....
- External blobs contain **no energy** (as compared to the jet)
- I.e. external blobs must be able to **trigger an intensive interaction**. To be heavy?
- Compact and heavy, i.e **DENSE:**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

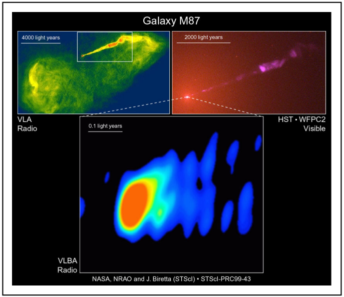
Specific realization of such blob formation:

Jet-Red Giant Interaction Scenario

VHE variability in M87

M87 observations





The parameters of the M87 BH and Jet

$$M_{BH} \simeq 6.4 \times 10^9 M_{\odot}$$

$$L_{jet} \simeq (1-5) \times 10^{44} \text{ergs s}^{-1}$$

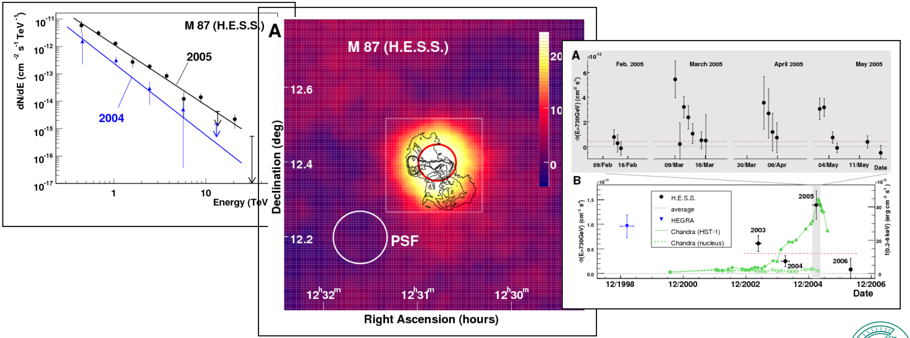
$$\text{radiative active region (in radio) } r \lesssim 10^{17} \text{cm}$$

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

Several flashes were observed in 2006, 2008, 2010.

Variability on scales $t \sim 1$day

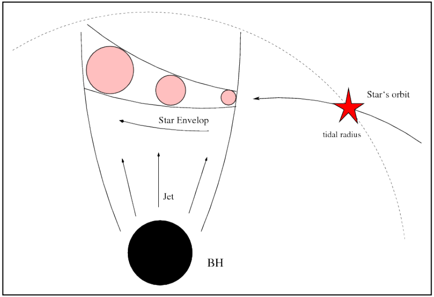
The flux $L_\gamma \sim 10^{42}$ergs s^{-1} $\qquad E_{\gamma,max} \simeq 20$TeV.

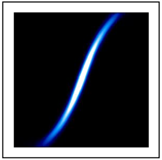


(Aharonian et al 2006; Abramowski et al. 2011; Aliu et al. 2011)

Tidal interaction

- In the case of FRI galaxies the ram pressure of the jet is not enough to destroy the RG outer layers.
- If the star approaches closer to the BH than the tidal disrution radius $z_T = R_{RG} \left(\frac{M_{BH}}{M_{RG}}\right)^{1/3}$, the outer layers of the star can be ablated by the jet.



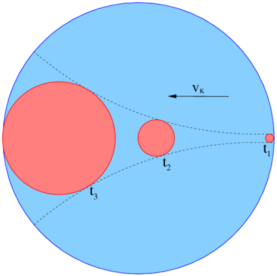


(Barkov et al 2010; Lodato et al. 2009)

Star envelop evolution

$$p_{\rm j} = \frac{F_{\rm j}}{c} \approx p_{\rm c} \qquad F_{\rm j} = \frac{L_{\rm j}}{\pi z_{\rm jc}^2 \theta^2} \approx 10^{14} \mathrm{erg\ cm^{-2}\ s^{-1}}$$

$$r_{\rm c}(t) = \frac{r_{\rm c0}}{(1 - t/t_{\rm ce})^2} \qquad t_{\rm ce} = 5\left(M_{\rm c28}/F_{j,14} r_{\rm c0,13}\right)^{1/2} \mathrm{days},$$

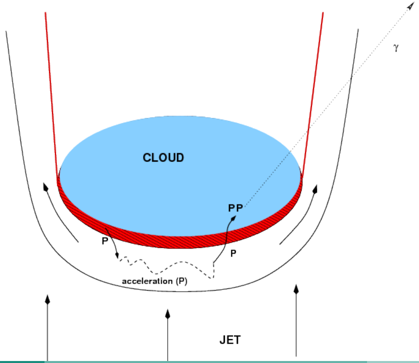


(Barkov et al 2010)

p-p interaction

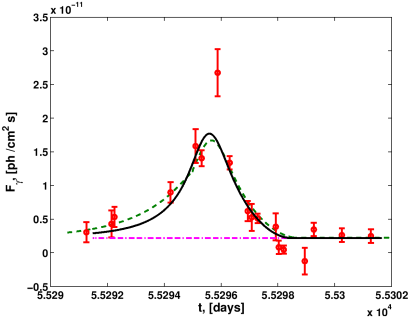
The cloud density can be very high making the *pp* interactions to be the most plausible mechanism for the gamma-ray production in the RG-jet interaction scenario: in this case the characteristic cooling time for *pp* collisions is

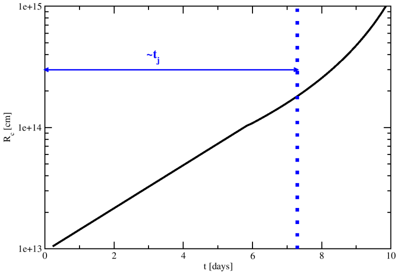
$$t_{pp} \approx \frac{10^{15}}{c_f n_c} = 10^5 \, n_{c,10}^{-1} c_f^{-1} \, \mathrm{s} \qquad \chi \equiv E_\gamma / E_p = 0.17 \left[2 - \exp(-t_v / t_{pp}) \right]$$



VHE light curve and the cloud evolution (Analytical model)

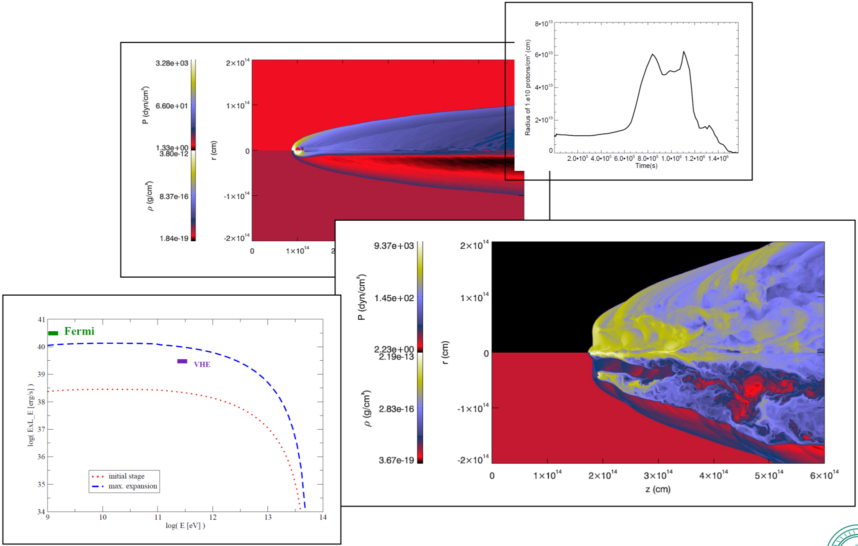
The adopted parameter values are: $L_j = 5 \times 10^{44}$ erg s^{-1}, $M_{BH} = 6.4 \times 10^9 \, M_\odot$, $r_c = 10^{13}$ cm, $\theta_{-1} = 0.5$, $M_{RG} = 1 \, M_\odot$, $z_{jc} \approx 3 \times 10^{16}$ cm, $M_c \approx 2 \times 10^{29}$ gr.





April 2010 flare
(Barkov et al 2012b)

Star envelop evolution (Numerical results)



(Bosch-Ramon et al 2012)

Star envelop evolution (Numerical results)

Uniform cloud

(Bosch-Ramon et al 2012)

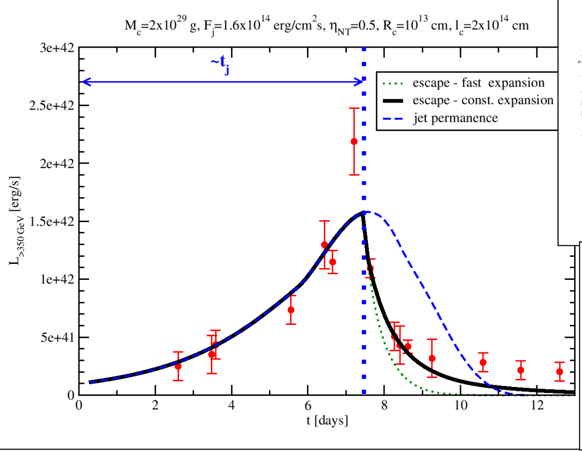
Star envelop evolution (Numerical results)

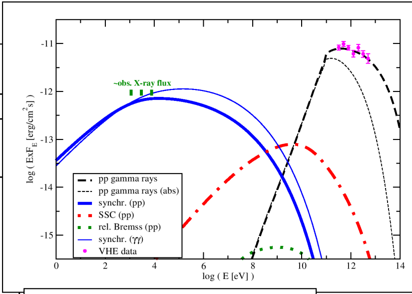
Star + Wind

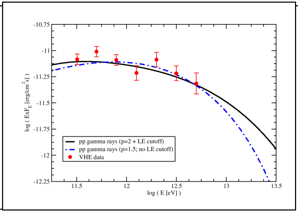
(Bosch-Ramon et al 2012)

VHE light curve and spectra (Numerical model)

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



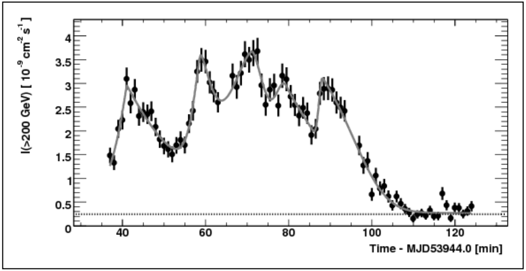


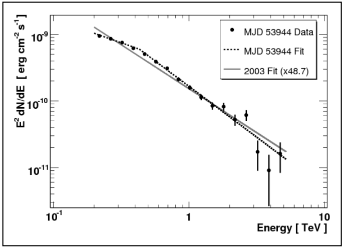


(Barkov et al 2012b)

Very fast variability in TeV blazars

PKS 2155–304 observations





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

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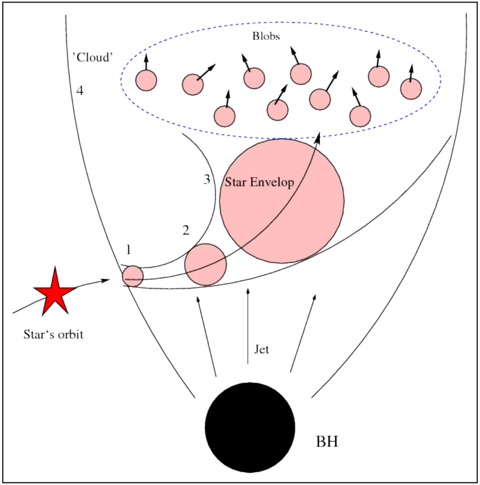
(Aharonian et al 2007)

AGN Jet – Red Giant interaction

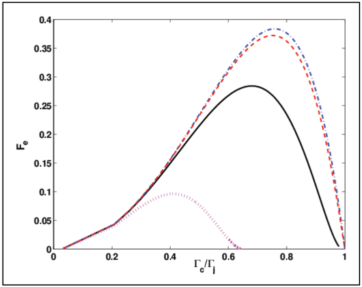


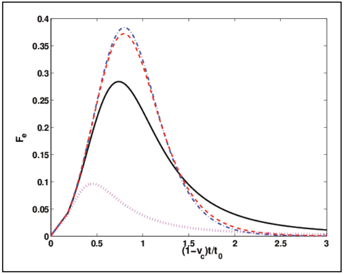
Schematic illustration of the scenario. When a star crosses the AGN jet, the outer layers of its atmosphere are ablated due to the high jet ram pressure.
(Barkov et al 2012a)

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 ($t_0 = z_0/2D\Gamma_j^2 c$). : $D = 100$, 10, 1 and 0.1. (Barkov et al 2012a)

Cloud and Blobs mass limitation

We can formulate the limit on the blob/cloud mass:

$$M_{\rm c,rc} \approx 0.5 \times 10^{26} L_{\rm j,46} r_{\rm c,15}^{2} D^{-1} \Gamma_{j,1.5}^{-3} M_{\rm BH,8}^{-1}\,{\rm g}.$$

The extreme value of $M_{\rm c,rc}$ can be achieved at $r_c \approx \omega$:

$$M_{\rm c,rc} \approx 2 \times 10^{26} L_{\rm j,46} M_{\rm BH,8} D^{-1} \Gamma_{j,1.5}^{-1}\,{\rm g}.$$

Energy Budget of the Cloud

The radiation of blazars is strongly Doppler boosted.

$$L_\gamma = L_{sc}\delta_{\rm c}^4 = \left(\frac{1}{\Gamma_{\rm c}^2} - \frac{\Gamma_{\rm c}^2}{\Gamma_{\rm j}^4}\right)\frac{\delta_{\rm c}^4 \xi L_{\rm j} r_{\rm c}^2}{4\omega^2}$$

The size of the blob:

$$r_{\rm c} \geq 5\times 10^{14} M_{\rm BH,8} L_{\gamma,47}^{1/2} L_{\rm j,46}^{-1/2} \xi_{-1}^{-1/2}\ \text{cm}$$

Maximum apparent luminosity of the blob, if $r_{\rm c} \approx \omega$:

$$L_{\gamma\rm max} = 2\times 10^{48} \xi_{-1} L_{\rm j,46} \Gamma_{\rm j,1.5}^2\, \rm erg\, s^{-1}.$$

The total energy of electromagnetic radiation which can be emitted by the cloud

$$E_{\rm tot} \approx 10^{50} \xi_{-1} M_{\rm c,25} \Gamma_{j,1.5}^3\, \rm erg.$$

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. $\omega^2/r_c^2 \sim 1$), 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:

$$\Delta t \approx 60\Gamma_{j,1.5} L_{\rm j,46}^{-1} M_{\rm c,25}\,{\rm s}$$

Restrictions for SSC

Magnetic field

$$B_0 = 0.7 \nu_{16}^2 E_{\gamma,11}^{-1} \delta^{-1} \text{ G}.$$

Ram pressure in the jet

$$P_{\text{ram,SSC}} \approx \frac{B_0^2 \Gamma_{\text{j}}^2}{8\pi} \approx 5 \times 10^{-3} \nu_{16}^4 E_{\gamma,11}^{-2} \, \text{dyn}, \text{cm}^{-2},$$

Cloud Lorentz factor

$$\Gamma_c \sim 300 L_{X,46}^{1/4} \tau_2^{-1/2}.$$

It is rather difficult to reach such a high value of the bulk Lorentz factor, e.g. due to the so called “photon breeding mechanism” (Stern & Poutanen 2006). All AGN jets have bulk Lorentz factors < 60.

Restrictions for EIC

Cooling Time

$$t'_{\rm cool} = 3 \times 10^3 (1+f)^{-1} z_{17}^{7/4} L_{\rm j,46}^{-3/4} M_{\rm BH,8}^{-1/4} \nu_{16}^{-1/2} \, {\rm s} \, .$$

Thomson regime

$$z_{17} \gg L_{\rm j,46}^{1/3} M_{\rm BH,8}^{1/3} E_{\gamma,11}^{4/3} \nu_{16}^{-2/3} \, .$$

Klein-Nishina regime

$$\tau_{\gamma\gamma} = z n_{\rm ext} \sigma_{\gamma\gamma} \approx 40 M_{\rm BH,8} \tau_2^{-1} \, ,$$

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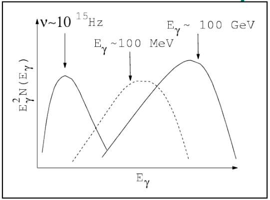
Proton-synchrotron in a Powerful jet



Maximum Energy

$$E_{\gamma,11} \approx 1\, B_2 E_{19}^2 , \qquad E_{\gamma,\max} \approx 400\eta^{-1}\delta \text{ GeV} .$$

Hillas Criterion

$$z_{17}^{3/2} L_{\gamma,47}^{-1/2} L_{j,46}^{-1/4} \eta_1^{-1/2} \xi_{-1}^{1/2} M_{BH,8}^{-1} < 0.1 .$$

Cooling Time

$$\tau_{psyn} \approx \frac{t_{sy}}{\delta} \approx 2 \times 10^4 \eta_1^{1/2} M_{BH,8}^{1/2} z_{17} L_{j,46}^{-3/4} \text{ s} .$$

EIC model for PKS 2155−304

Constraints

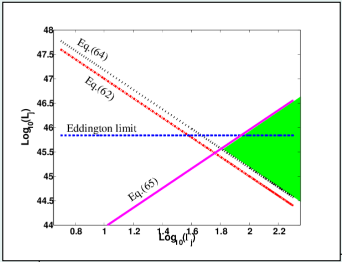
$$L_{\mathrm{j},46} > 0.5\frac{1}{\xi_{-1} M_{\mathrm{BH},8}\Gamma^2_{\mathrm{j},1.5}}\,,$$

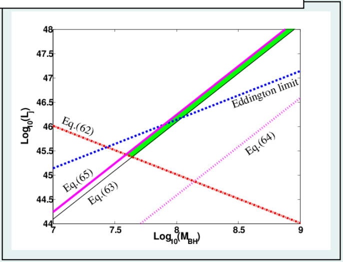
$$L_{\mathrm{j},46} > 30\frac{M^2_{\mathrm{BH},8} L_{\gamma,47}}{\tau_2^2 \Gamma^2_{\mathrm{j},1.5}\xi_{-1}}\,,$$

$$L_{\mathrm{j},46} > 0.007\frac{M^2_{\mathrm{BH},8}\Gamma^{10/3}_{\mathrm{j},1.5}}{\tau_2^{4/3}\nu_{16}^{2/3}}\,,$$

$$L_{\mathrm{j},46} \ll 0.4\frac{M^2_{\mathrm{BH},8}\Gamma^6_{\mathrm{j},1.5}\nu^2_{16}}{E^4_{11}}\,.$$

Parameter space





Proton-synchrotron model for PKS 2155−304

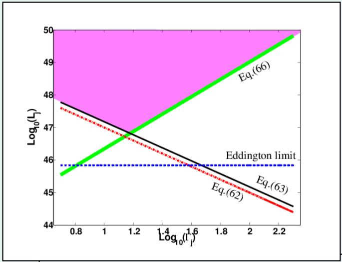
Constraints

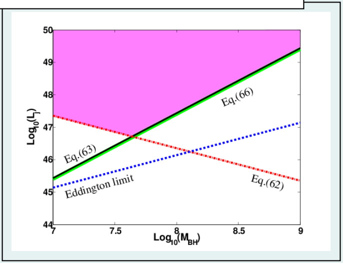
$$L_{\mathrm{j},46} > 0.5 \frac{1}{\xi_{-1} M_{\mathrm{BH},8} \Gamma^2_{\mathrm{j},1.5}} ,$$

$$L_{\mathrm{j},46} > 30 \frac{M^2_{\mathrm{BH},8} L_{\gamma,47}}{\tau_2^2 \Gamma^2_{\mathrm{j},1.5} \xi_{-1}} ,$$

$$L_{\mathrm{j},46} > 500 \frac{M^2_{\mathrm{BH},8} \Gamma^{8/3}_{\mathrm{j},1.5} \eta_1^{2/3}}{\tau_2^{4/3}} .$$

Parameter space





Discussion: event frequency

- An important question is whether there are enough RGs at the relevant jet scales.

$$n \sim 10^6 \Upsilon M_{\rm BH,8}^{-1/2} \theta_{-1}^{-1} z_{17}^{-3/2} {\rm pc}^{-3} .$$

- Clouds from BLR also can penetrate to the jet and produce γ-ray flares.

Discussion: event frequency

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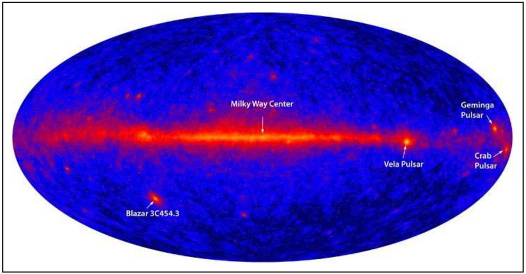
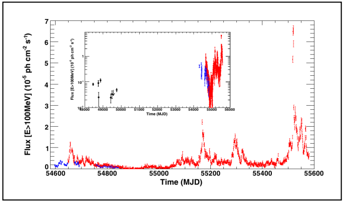
- Clouds from BLR also can penetrate to the jet and produce γ-ray flares.

Very fast variability in GeV blazars (3C454.3)

3C454.3 observations





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

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

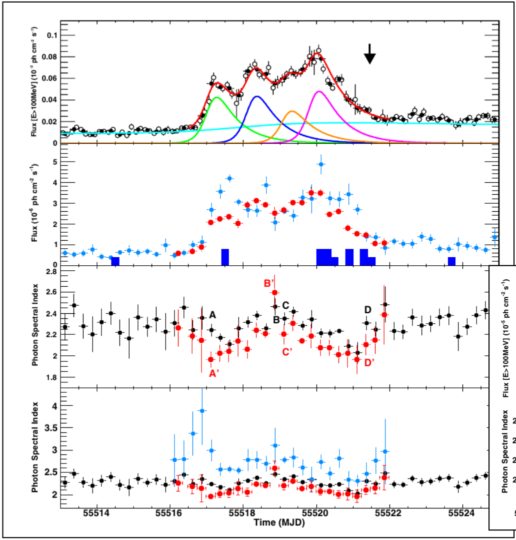
$$\tau_r \approx 4.5 \text{ h}$$

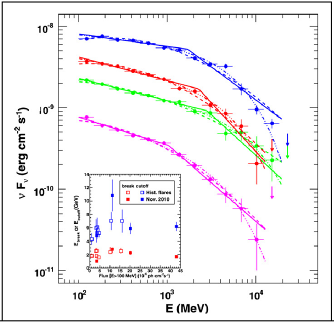
$$L_X \sim 5 \times 10^{47} \text{erg s}^{-1}$$

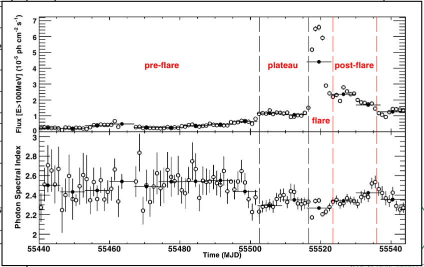
(Abdo et al. 2011; Vercellone et al. 2011)

3C454.3 observations

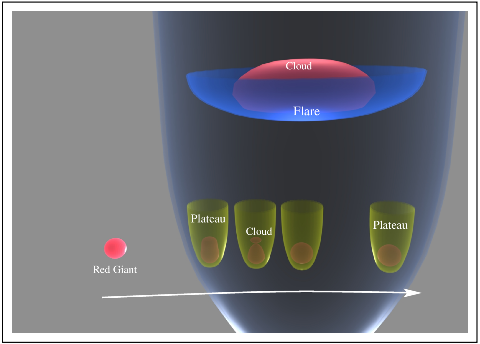
(Abdo et al 2011)







Sketch and Plateau model



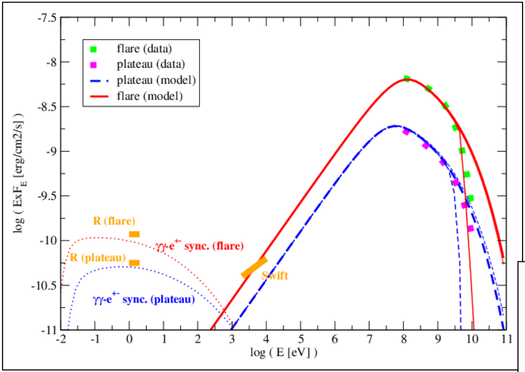
$$\dot{M}_* \approx 10^{24} L_{\gamma,49} \xi_{-1}^{-1} \Gamma_{j,1.5}^{-3} \text{ g/s.}$$

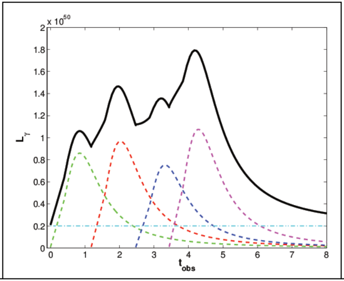
The cosmic ray/X-ray exited stellar wind allows us to estimate stellar radius

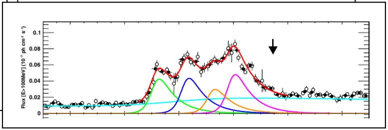
$$R_* \approx 200 \left(\frac{L_{\gamma,49} M_{\rm BH,9}^2 M_{*,0}^{1/2}}{\Gamma_{\rm j,1.5} L_{\rm j,49}} \right)^{2/5} R_\odot \,,$$

(Barkov et al 2012c)

Radiation Model: Electron synchrotron + secondary synchrotron







$$L_j \approx 10^{49} \mathrm{erg\ s}^{-1}$$

$$M_{BH} \approx 10^9 M_\odot \qquad \Gamma_j \approx 30$$

(Barkov et al 2012c)

Conclusions

- The jet can blow-up the RG envelope fragments and accelerate them up to Lorentz factors of Γ_j (~ 30).
- In the case of PKS 2155−304 the radiation in the TeV energy range can be effectively produced through proton synchrotron radiation or EIC in the Thompson regime.
- In the case of 3C454.3 the radiation in the GeV energy range can be effectively produced through electron synchrotron radiation.
- The model can explain the minute-scale TeV flares on top of a longer (typical time-scales of days) gamma-ray variability.
- 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.

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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); submited to ApJ, arXiv:1202.5907
- MVB, V. Bosch-Ramon D.V. Khangulyan, F.A. Aharonian and A. Dorodnitsyn, (3C454.3) prepared for ApJ, arXiv:

Thank you!!!