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

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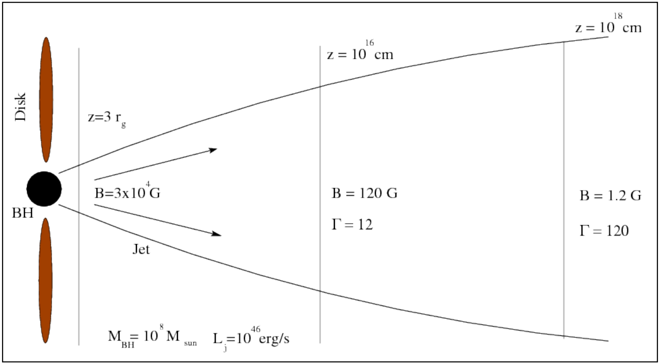
Outline

1. Structure of the Magnetically driven jet
2. VHE very short variability
3. Not Powerful Jet or very massive cloud (M87)
4. Powerful Jet with low mass cloud (PKS 2155−304)
5. Powerful Jet with massive cloud (3C454.3)
6. Conclusions

Structure of the Magnetically driven Jet

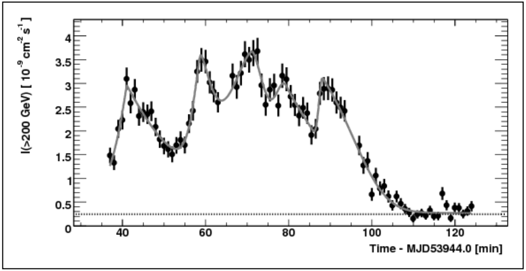
Sketch of the jet with characteristic magnetic field strengths and bulk Lorentz factors at typical distances from a BH with mass $M_{BH} = 10^8 M_\odot$ and $L_j = 10^{46}$ erg s^{-1}.

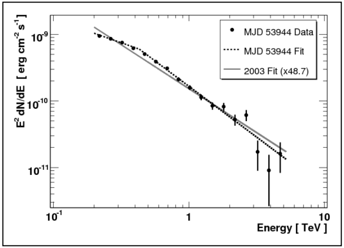


$$\Gamma_j = \frac{\omega}{4r_g}, \qquad \theta \sim \frac{1}{\Gamma_j}, \qquad B_c \approx \frac{2}{z}\left(\frac{L_j}{c}\right)^{1/2} G$$

(Komissarov et.al.,2007 & 2009; Beskin et.al., 2006; Lyubarsky 2011). Realistic jets are not uniform (see Komissarov et.al., 2009)

PKS 2155–304 observations





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

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

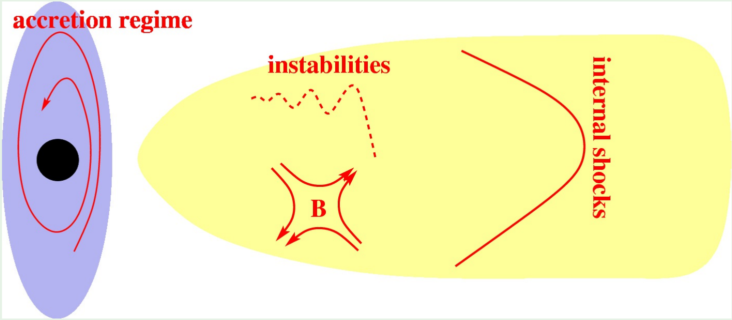
$$\tau \approx 200 \text{ s}$$

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

(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

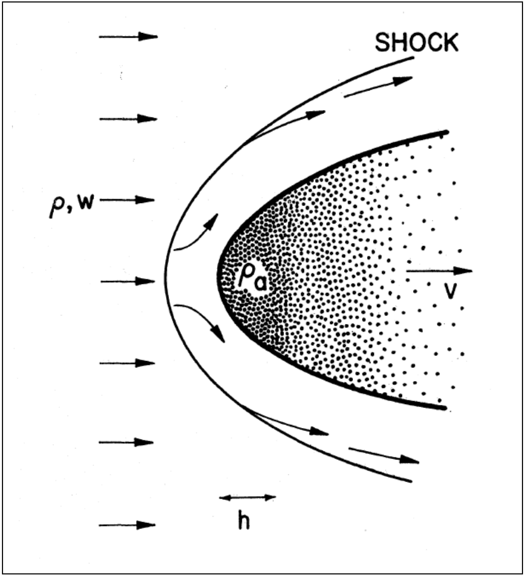
Blobs of external origin

- 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, BLR clouds?

Specific realization of such blob formation:

Jet-Red Giant Interaction Scenario

Cloud — Jet interaction

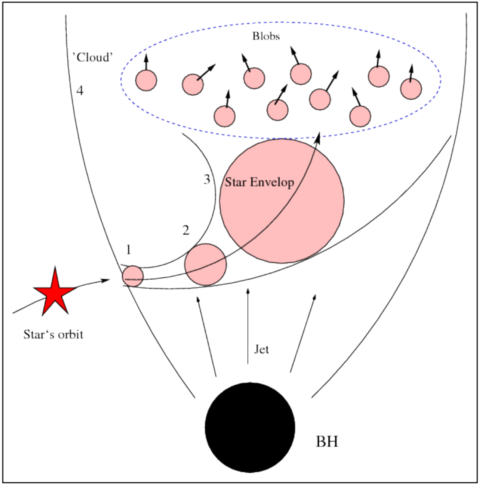


(Blandford & Königl 1979)

Cloud/Star — Jet interaction

- Not Powerful Jet or very massive cloud (M87)
- Powerful Jet with low mass cloud (PKS 2155−304)
- Powerful Jet with massive cloud (3C454.3)

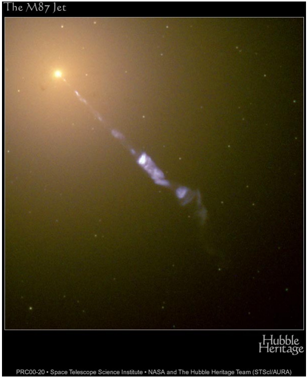
Cloud/Star — Jet interaction (Powerful Jet)

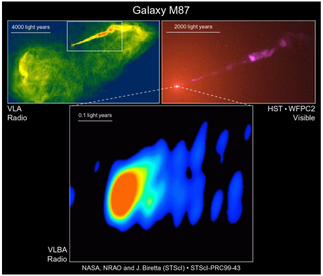


Schematic illustration of the scenario. When a star crosses the AGN jet, the outer layers of its atmosphere are ablated due to the high jet ram pressure.
(Barkov et al 2012a)

Not Powerful Jet or very massive cloud (M87)

M87 observations





The parameters of the M87 BH and Jet

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

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

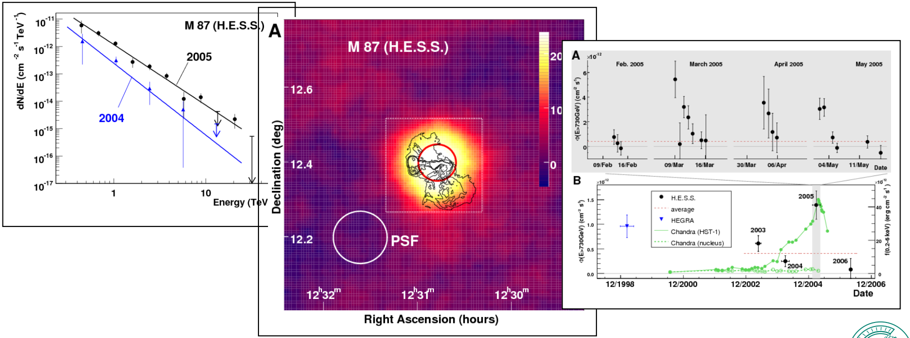
radiative active region (in radio) $r \lesssim 10^{17}$cm

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

Several flashes were observed in 2006, 2008, 2010.

Variability on scales $t \sim 1$day

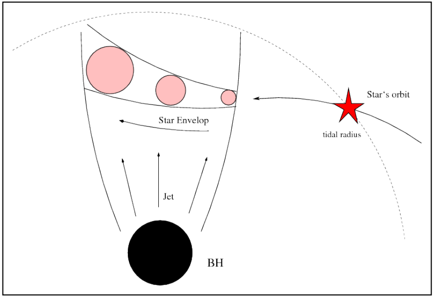
The flux $L_\gamma \sim 10^{42}$ergs s^{-1} $\quad E_{\gamma,max} \simeq 20$TeV.

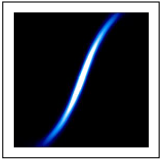


(Aharonian et al 2006; Abramowski et al. 2011; Aliu et al. 2011)

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 $z_{\rm T} = R_{\rm RG}\left(\frac{M_{\rm BH}}{M_{\rm RG}}\right)^{1/3}$, the outer layers of the star can be ablated by the jet.



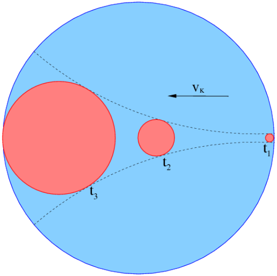


(Barkov et al 2010; Lodato et al. 2009)

Star envelop evolution

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

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

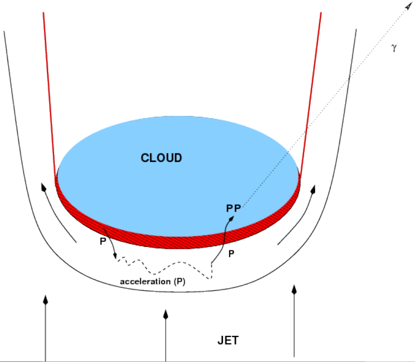


(Barkov et al 2010)

p-p interaction

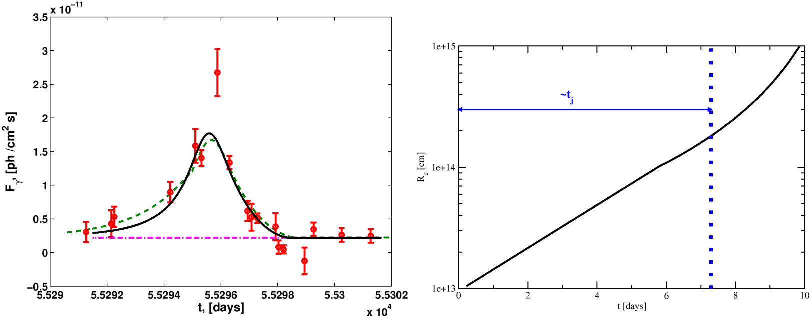
The cloud density can be very high making the *pp* interactions to be the most plausible mechanism for the gamma-ray production in the RG-jet interaction scenario: in this case the characteristic cooling time for *pp* collisions is

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



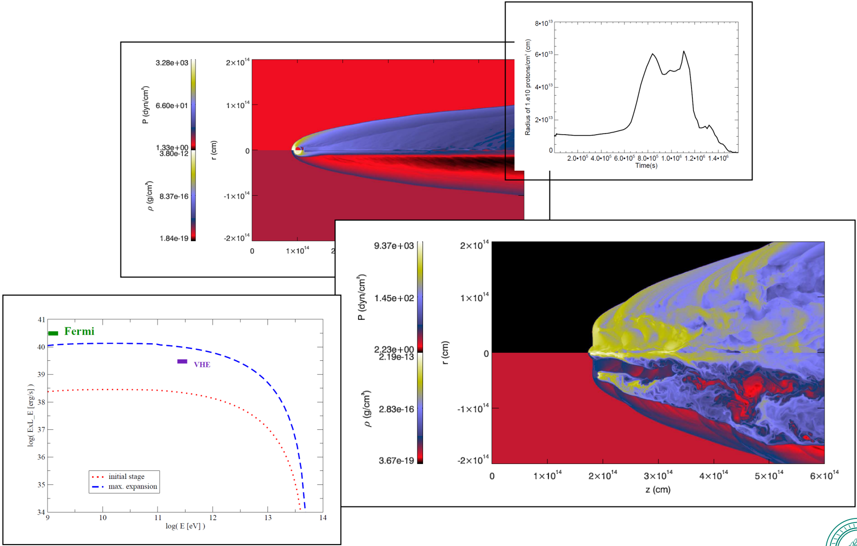
VHE light curve and the cloud evolution (Analytical model)

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



April 2010 flare (data from H.E.S.S., MAGIC and VERITAS)
(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)

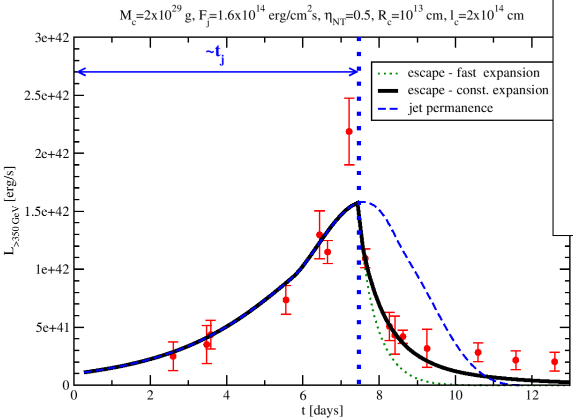
Star envelop evolution (Numerical results)

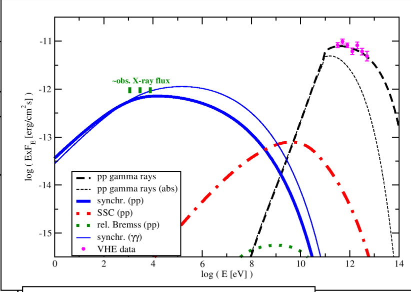
Star + Wind

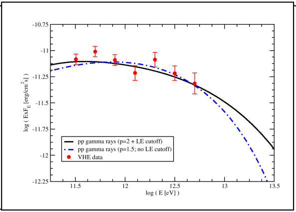
(Bosch-Ramon et al 2012)

VHE light curve and spectra (Numerical model)

$\xi = 0.5$ and $Q_{\rm p}(E) \propto E^{-2}$





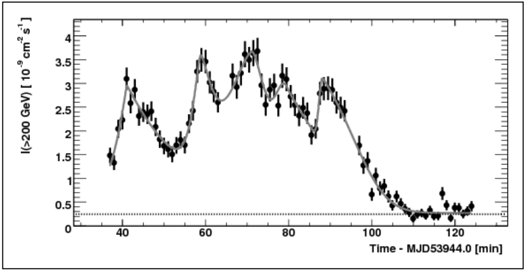


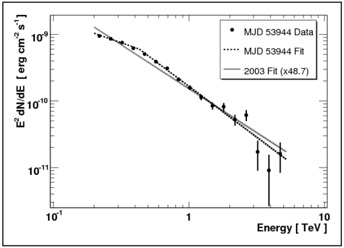
(Barkov et al 2012b)

Powerful Jet with low mass cloud (PKS 2155−304)

($D \gg 1$)

PKS 2155–304 observations





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

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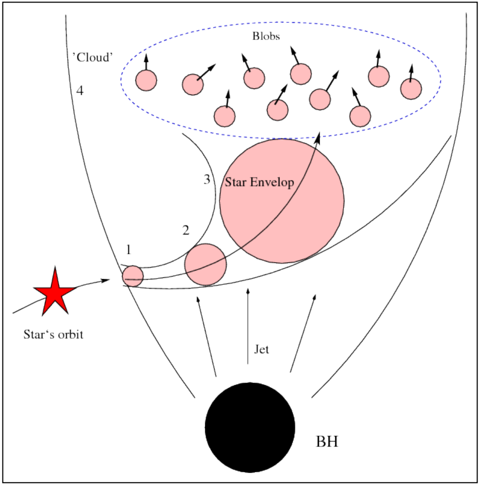
$$L_X \sim 10^{46} \text{erg s}^{-1}$$

(Aharonian et al 2007)

AGN Jet – Red Giant interaction

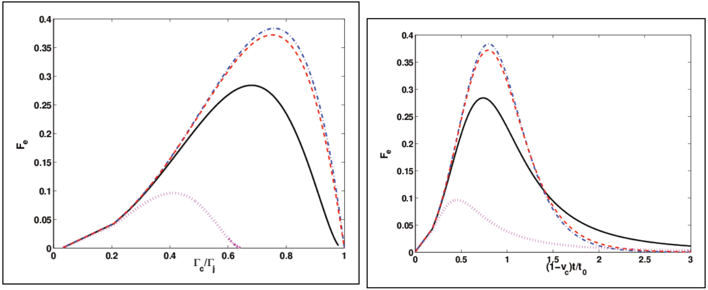


Schematic illustration of the scenario. When a star crosses the AGN jet, the outer layers of its atmosphere are ablated due to the high jet ram pressure.
(Barkov et al 2012a)

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:

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

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. $\omega^2/r_\mathrm{c}^2 \sim 1$), 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:

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

Restrictions for SSC

Magnetic field

$$B_{\rm c} = 0.7\nu_{16}^{2} E_{\gamma,11}^{-1}\delta^{-1}\ {\rm G}.$$

Ram pressure in the jet (if $B_{\rm c} \sim B_{\rm j}$)

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

Cloud Lorentz factor (if $B_{\rm c} \sim B_{\rm j}$)

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

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.

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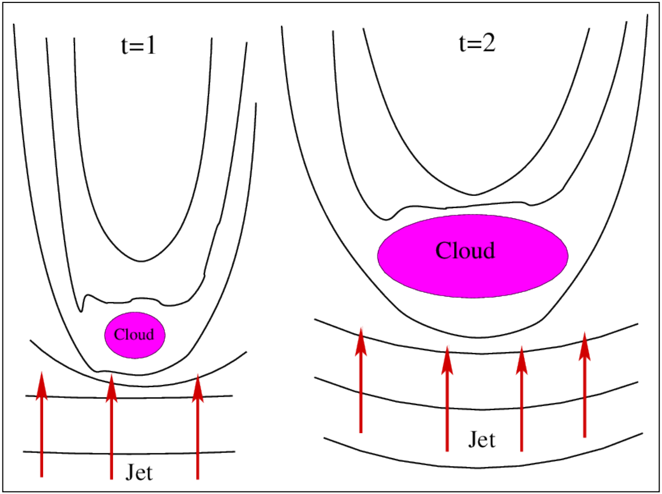
The magnetic field shielding



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

$B_c \ll B_j$

Restrictions for EIC

Cooling Time

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

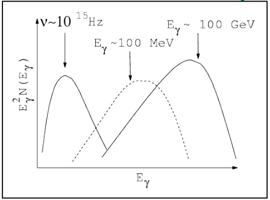
Thomson regime

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

Klein-Nishina regime

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

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

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

Cooling Time

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

EIC model for PKS 2155−304

Constraints

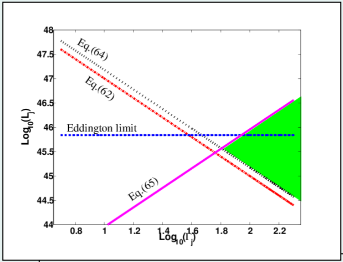
$$L_{j,46} > 0.5 \frac{1}{\xi_{-1} M_{BH,8} \Gamma^2_{j,1.5}} ,$$

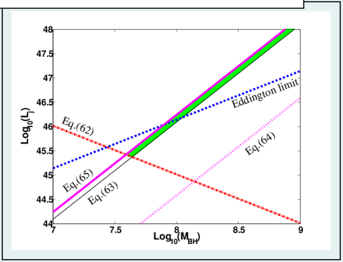
$$L_{j,46} > 30 \frac{M^2_{BH,8} L_{\gamma,47}}{\tau_2^2 \Gamma^2_{j,1.5} \xi_{-1}} ,$$

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

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

Parameter space





Proton-synchrotron model for PKS 2155−304

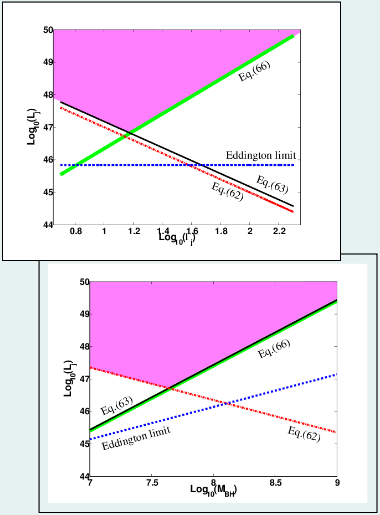
Constraints

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

$$L_{j,46} > 30 \frac{M_{BH,8}^2 L_{\gamma,47}}{\tau_2^2 \Gamma_{j,1.5}^2 \xi_{-1}} ,$$

$$L_{j,46} > 500 \frac{M_{BH,8}^2 \Gamma_{j,1.5}^{8/3} \eta_1^{2/3}}{\tau_2^{4/3}} .$$

Parameter space



Discussion: event frequency

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

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

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

Discussion: event frequency

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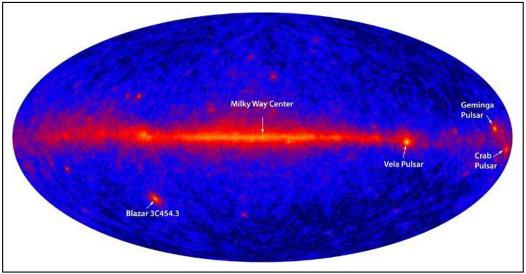
$$n \sim 10^6 \Upsilon M_{\rm BH,8}^{-1/2} \theta_{-1}^{-1} z_{17}^{-3/2} {\rm pc}^{-3} .$$

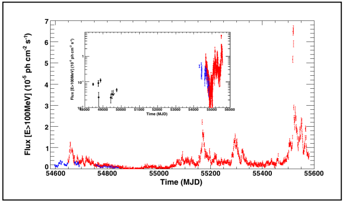
- Clouds from BLR also can penetrate to the jet and produce γ-ray flares.

Powerful Jet with massive cloud (3C454.3)

($D \ll 1$)

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)

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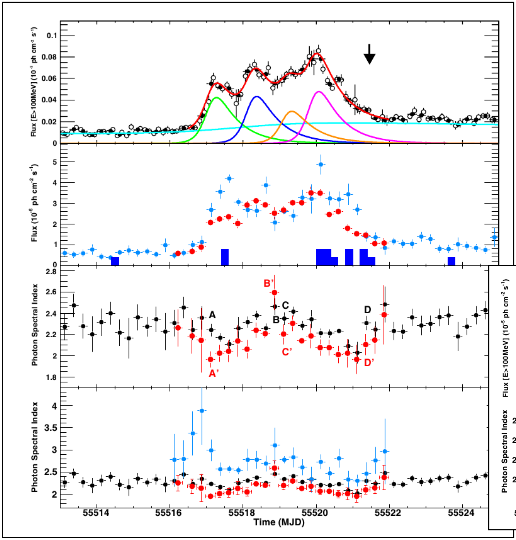
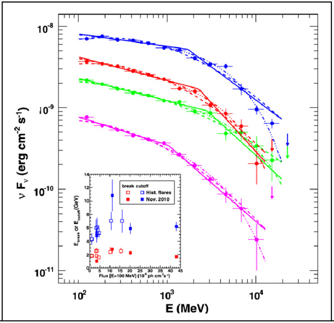
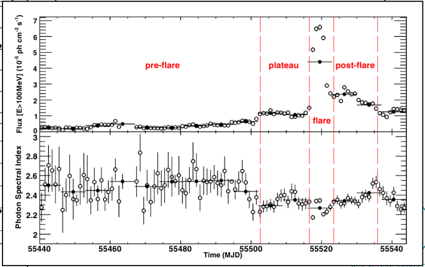
3C454.3 observations (2010 November)

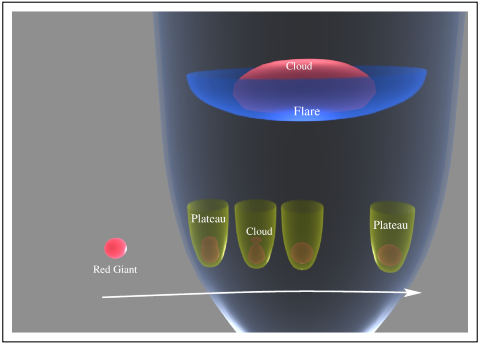
(Abdo et al 2011)







Sketch and Plateau model

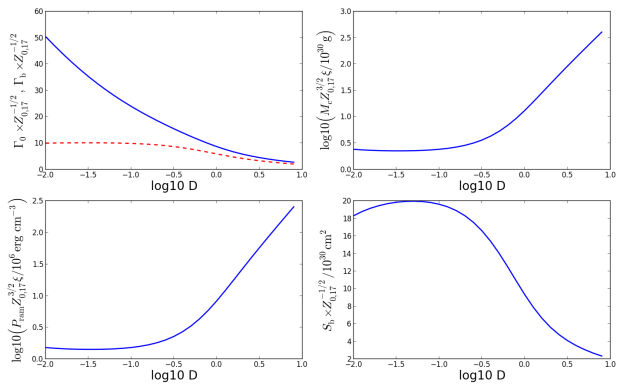


$$\dot{M}_* \approx 10^{24} L_{\gamma,49} \xi_{-1}^{-1} \Gamma_{j,1.5}^{-3} \text{ g/s.}$$

The cosmic ray/X-ray exited stellar wind (Basko et al. 1973; Dorodnitsyn et al. 2008), which allows us to make restriction on stellar radius

$$\dot{M} \approx 10^{24} \alpha_{-12} R_{*,2}^{5/2} M_{*,0}^{-1/2} \chi P_{0,6} \, \text{g s}^{-1} \quad \text{or} \quad \alpha_{-12}\chi \gtrsim 2 \bar{F}_{\rm e} R_{*,2}^{-5/2} M_{0,*}^{1/2} .$$

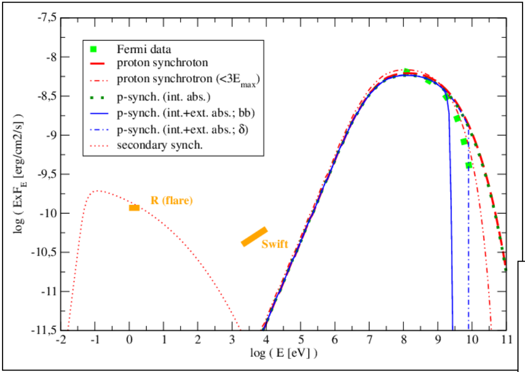
The Model Solution for the Main Flare

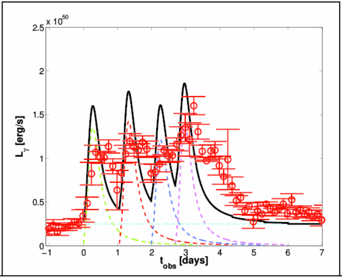


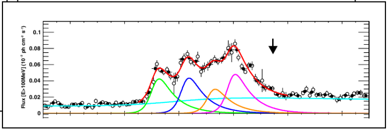
$$D \equiv \frac{L_j r_c^2}{4\theta^2 \Gamma_j^3 z_0 c^3 M_c} \qquad L_j \geq 10^{48} \quad \mathrm{erg\ s^{-1}}$$

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

Radiation Model: Proton synchrotron + secondary synchrotron

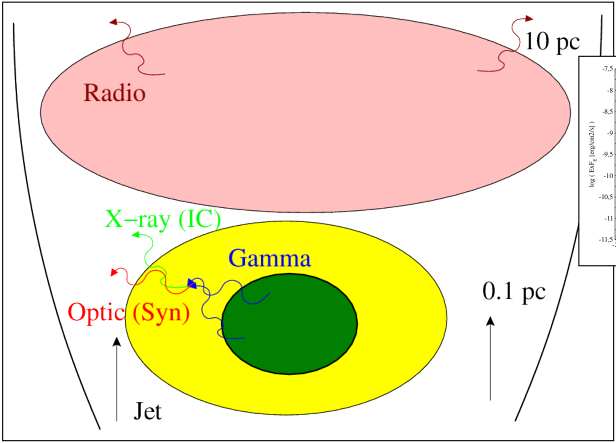


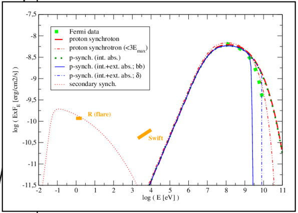




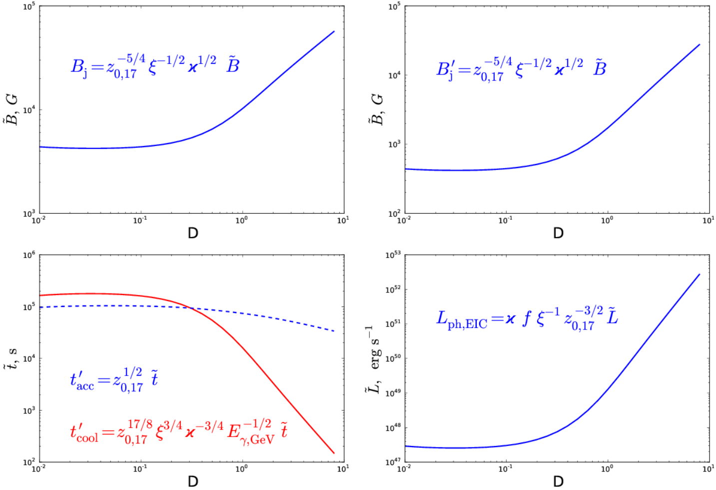
$$t_{acc}/(2\Gamma_b^2) \approx 5 \text{ h.}$$

Radiation Model: Geometry

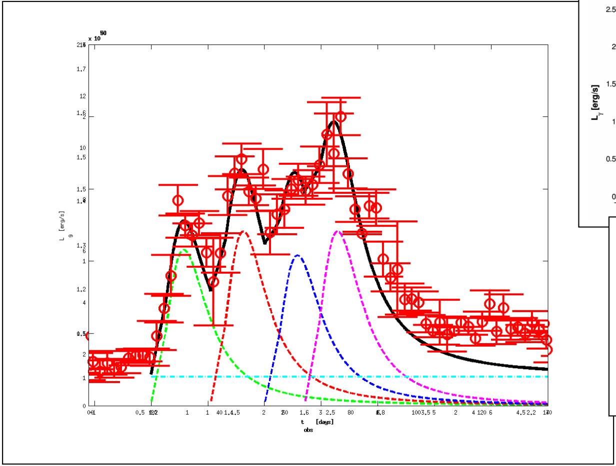


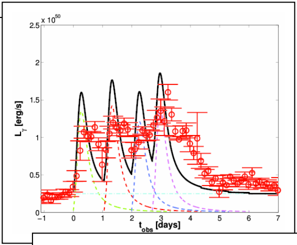


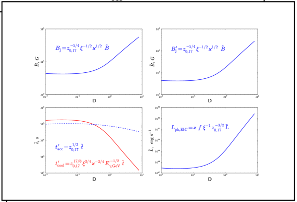
Radiation Model: limitations



Radiation Model: Light curve + cooling time







Conclusions

- The different regimes of the Cloud/Star — Jet interaction model can naturally explain various TeV and GeV variability in AGNs.
- In the cases of PKS 2155−304 and 3C454.3 the radiation in the TeV and GeV energy range respectively can be effectively produced through proton synchrotron radiation or EIC in the Thompson regime (with very low magnetization).
- In framework of cloud/star — jet interaction model we can explain the detected day-scale TeV flares in 2010 from M87 via proton-proton collisions.

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

MAX-PLANCK-GESELLSCHAFT

Thank you!!!