Particle acceleration and VHE emission of blazars

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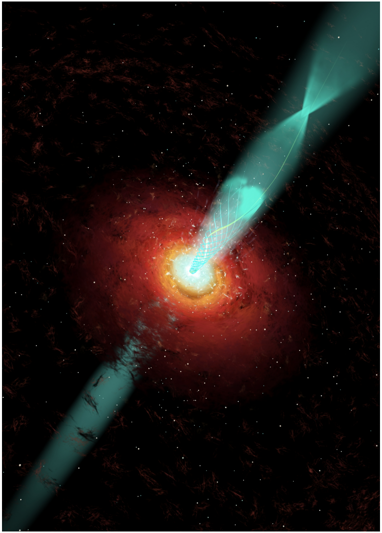
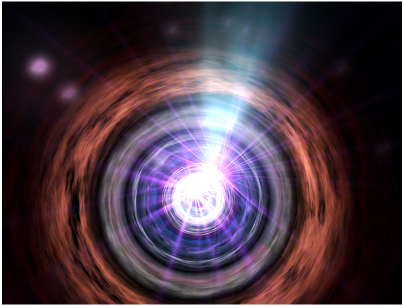
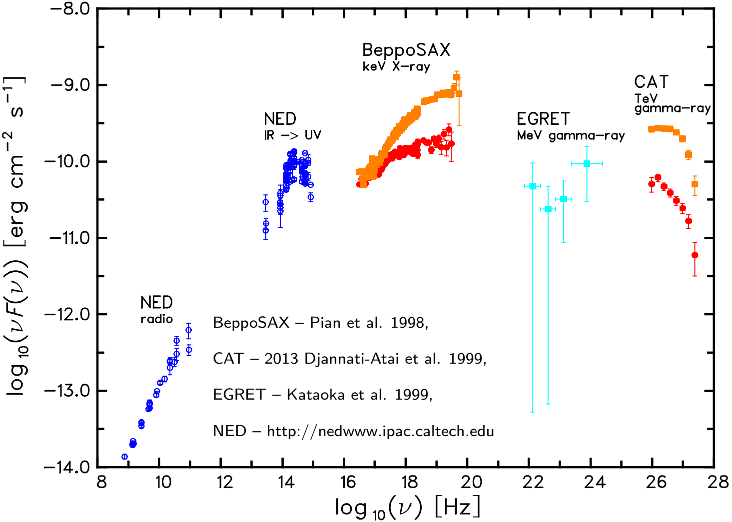
Blazars



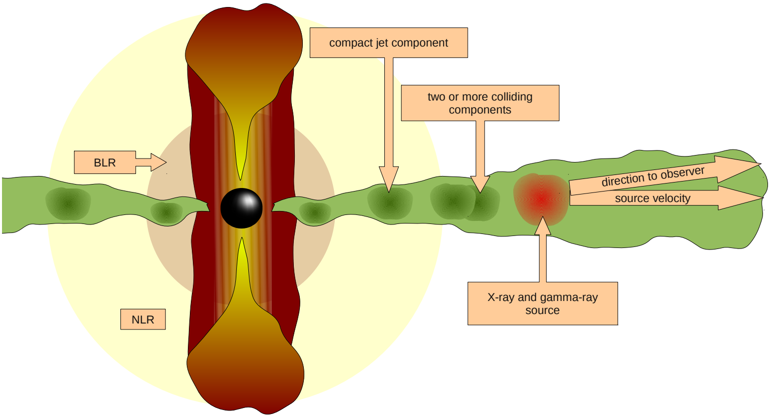


Jets in blazars are usually observed at very small angle. This explains rapid variability and relatively high level of the emission.

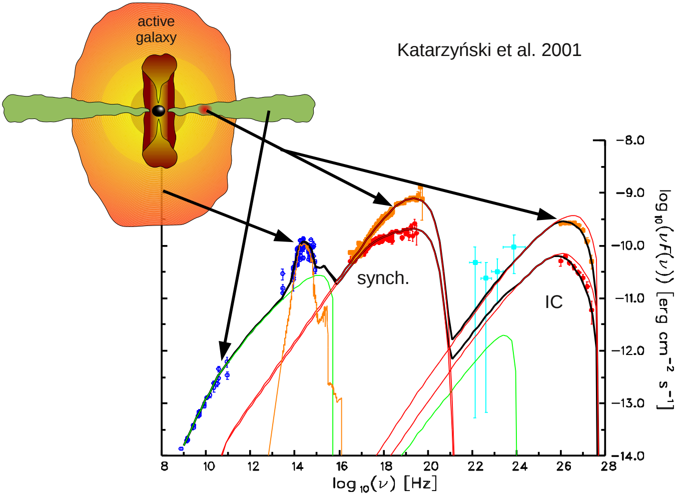
Spectrum of Mrk 501



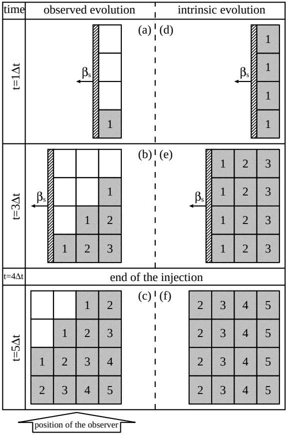
Internal shock scenario



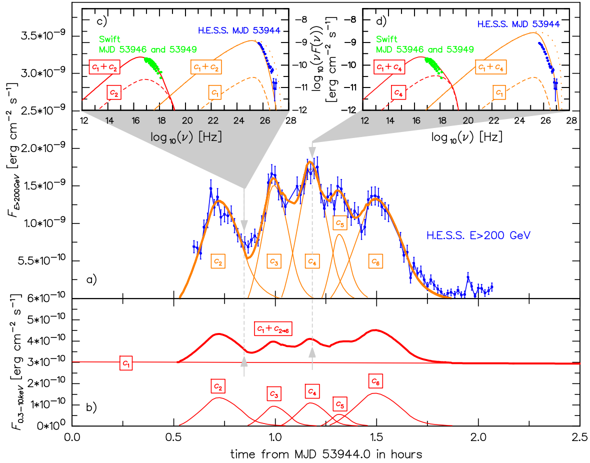
Mrk 501 – emission model



Rapid variability of PKS 2155-304 - particle injection model



Chiaberge & Ghisellini 1999



Aharonian et al. 2007, Katarzyński et al. 2008

Spectrum of Mrk 501 – acceleration and injection

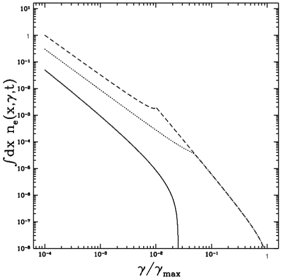


Fig. 1. The electron distribution integrated over the source, as given by Eq. (10). The three curves correspond to the times $5t_{acc}$ (solid line), $30t_{acc}$ (dotted line) and $500t_{acc}$, (dashed line). At larger times the distribution does not evolve appreciably. For this plot, $t_{esc} = 2t_{acc}$ (i.e., $s = 3.5$) and $t_b = 100t_{acc}$. At $t = 5t_{acc}$, no particles have had time to cool, since the cooling time at the maximum Lorentz factor of $\gamma \approx 0.025\gamma_{max}$ is approximately $40t_{acc}$. At times $t > 500t_{acc}$ all particles with $\gamma > \gamma_{max}t_{acc}/t_b$ cool, whereas those of lower γ leave the source without significant loss of energy.

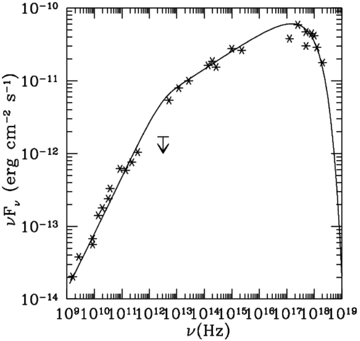


Fig. 2. The radio – X-ray spectrum of the object Mkn 501 (data taken from the collation of Catanese et al. 1997) together with the stationary synchrotron emission from a single homogeneous source

Kirk, Rieger & Mastichiadis 1998

Acceleration & injection – description of the model

The number $N(\gamma)\mathrm{d}\gamma$ of particles with Lorentz factor between γ and $\gamma+\mathrm{d}\gamma$ in the acceleration zone around the shock is governed by the equation

$$\frac{\partial N}{\partial t}+\frac{\partial}{\partial\gamma}\left[\left(\frac{\gamma}{t_{\mathrm{acc}}}-\beta_{\mathrm{s}}\gamma^2\right)N\right]+\frac{N}{t_{\mathrm{esc}}} = Q\delta(\gamma-\gamma_0) \quad (1)$$

(Kirk et al. 1994), where

$$\beta_{\mathrm{s}} = \frac{4}{3}\frac{\sigma_{\mathrm{T}}}{m_{\mathrm{e}}c}\left(\frac{B^2}{2\mu_0}\right). \quad (2)$$

with $\sigma_{\mathrm{T}} = 6.65\cdot 10^{-29}\mathrm{m}^2$ the Thomson cross section. The first term in brackets in Eq. (1) describes acceleration at the rate t_{acc}^{-1}, the second describes the rate of energy loss due to synchrotron radiation averaged over pitch-angle (because of the isotropy of the distribution) in a magnetic field B (in Tesla). Particles are assumed to escape from this region at an energy independent rate t_{esc}^{-1}, and to be picked up (injected) into the acceleration process with Lorentz factor γ_0 at a rate Q particles per second.

The kinetic equation governing the differential density $\mathrm{d}n(x,\gamma,t)$ of particles in the range $\mathrm{d}x$, $\mathrm{d}\gamma$ is then

$$\frac{\partial n}{\partial t}-\frac{\partial}{\partial\gamma}(\beta_{\mathrm{s}}\gamma^2 n) = \frac{N(\gamma,t)}{t_{\mathrm{esc}}}\delta(x-x_{\mathrm{s}}(t)) \quad (6)$$

where $x_{\mathrm{s}}(t)$ is the position of the shock front at time t. For a shock which starts to accelerate (and therefore 'inject') particles at time $t=0$ and position $x=0$ and moves at constant speed u_{s},

Kirk, Rieger & Mastichiadis 1998

The momentum–diffusion equation

Stochastic acceleration process can be described as the diffusion in the particle momentum space, where the evolution of the isotropic, homogeneous phase–space density ($f(p,t)$) is described by the momentum–diffusion equation

$$\frac{\partial f(p,t)}{\partial t} = \frac{1}{p^2}\frac{\partial}{\partial p}\left[p^2 D(p,t)\frac{\partial f(p,t)}{\partial p}\right],$$

where $p = \beta\gamma$ is the dimensionless particle momentum, $D(p,t)$ is the momentum–diffusion coefficient, γ it the particle Lorentz factor and β is the particle velocity in units of c.

Transformation of the equation

The particle number density (N [cm^{-3}]) is directly related to the phase–space density

$$N(p,t) = 4\pi p^2 f(p,t).$$

Thus, we can rewrite the equation

$$\frac{\partial N(p,t)}{\partial t} = \frac{\partial}{\partial p}\left[-A(p,t)\; N(p,t) + D(p,t)\frac{\partial N(p,t)}{\partial p}\right],$$

where

$$A(p,t) = \frac{2}{p} D(p,t),$$

describes the acceleration process.

Three more terms in the equation

In order to describe the radiative cooling and possible escape or injection of the particles we have to introduce three more terms

$$\frac{\partial N(\gamma,t)}{\partial t} = \frac{\partial}{\partial\gamma}\left[\Big(C(\gamma,t) - A(\gamma,t)\Big)N(\gamma,t) + D(\gamma,t)\frac{\partial N(\gamma,t)}{\partial\gamma}\right] - \frac{N(\gamma,t)}{t_{\rm esc}} + Q(\gamma,t).$$

Note that for the relativistic particles ($\beta \simeq 1$) the particle momentum becomes equivalent to the Lorentz factor ($p \equiv \gamma$).

The stationary solution

The stationary ($\dot{N} = 0$) analytic solution of the equation in a simplified form

$$\frac{\partial}{\partial \gamma}\left[\Big(C(\gamma) - A(\gamma)\Big)N(\gamma) + D(\gamma)\frac{\partial N(\gamma)}{\partial \gamma}\right] = 0,$$

according to Chang and Cooper (1970), is given by

$$N(\gamma) = x \;\; \exp\left[-\int^{\gamma} \frac{C(\gamma') - A(\gamma')}{D(\gamma')} d\gamma'\right],$$

where x is the integration constant. Note that the above equation requires that the initial energy distribution $\boxed{N(\gamma, t = 0) \neq 0}$

Thermal spectrum

Assuming a constant synchrotron cooling

$$C(\gamma) = C_0 \gamma^2,$$

and Fermi-like constant acceleration process

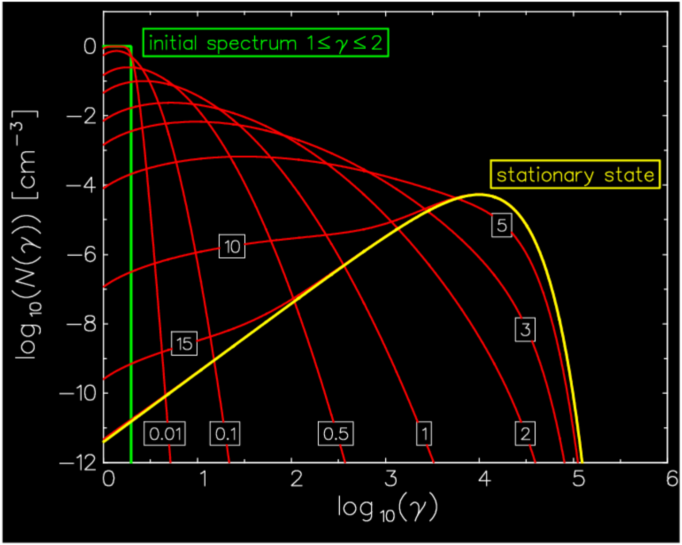
$$D(\gamma) = \frac{\chi}{2}\gamma^2 = \frac{\gamma^2}{(2t_{\rm acc})} \quad \rightarrow \quad A(\gamma) = \frac{\gamma}{t_{\rm acc}},$$

we obtain an ultra-relativistic Maxwellian distribution

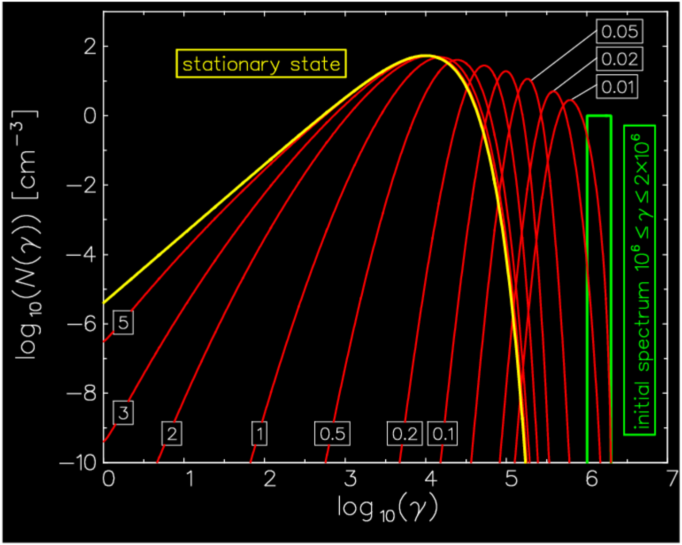
$$\boxed{N(\gamma) = x\, \gamma^2 \ \exp\left[-2 C_0 t_{\rm acc}(\gamma - 1)\right]}$$

where the maximum appears at the equilibrium between the cooling and heating (Schlickeiser 1984).

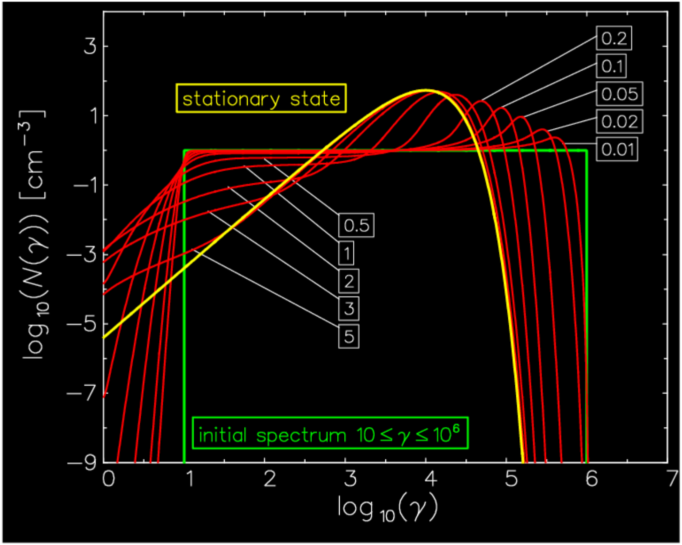
Evolution without injection & escape – example 1



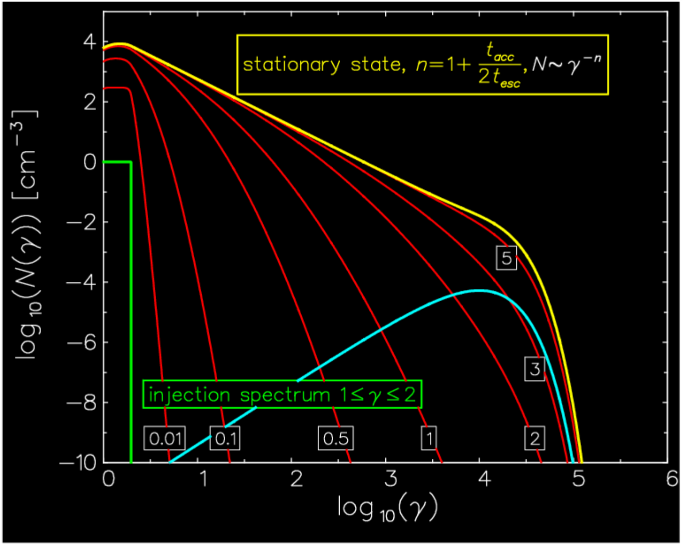
Evolution without injection & escape – example 2



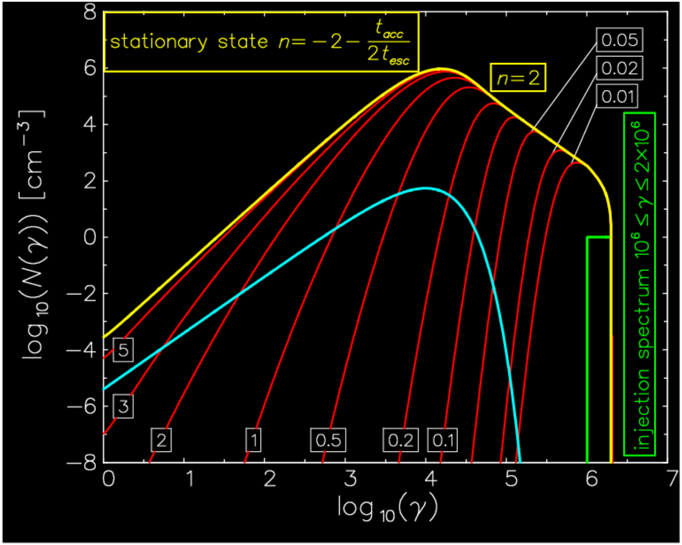
Evolution without injection & escape – example 3



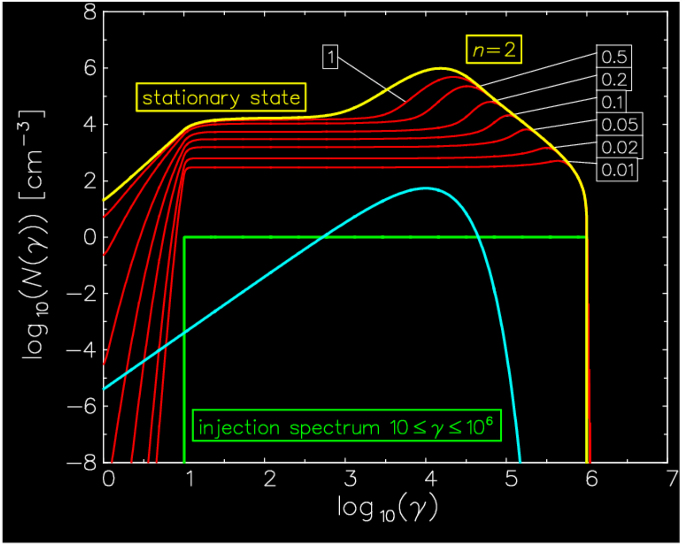
Evolution with injection & escape – example 1



Evolution with injection & escape – example 2



Evolution with injection & escape – example 3



Radiative cooling due to the SSC emission

The synchrotron and inverse Compton cooling is described by

$$C(\gamma) = \frac{4}{3}\frac{\sigma_T c}{m_e c^2}\left[U_B + U_{\rm rad}(\gamma)\right]\gamma^2,$$

where

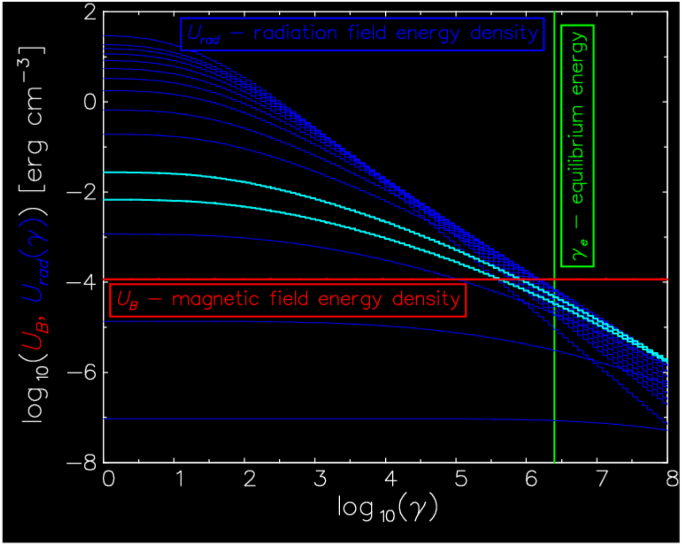
$$U_B = \frac{B^2}{8\pi},$$

is the magnetic field energy density and

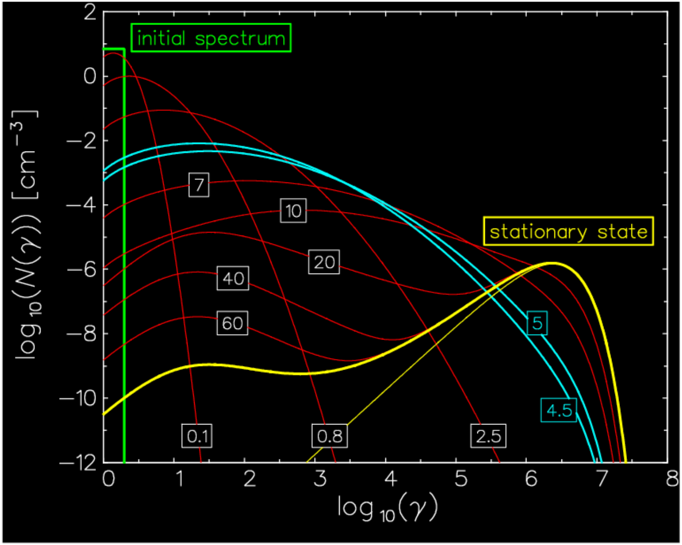
$$U_{\rm rad}(\gamma) \simeq \frac{4\pi}{c}\int_{\nu_{\rm min}}^{\nu_x(\gamma)} I_{\rm syn}(\nu)d\nu \quad \nu_x = \min\left[\nu_{\rm max}, \frac{3m_e c^2}{4h\gamma}\right]$$

is the radiation field energy density.

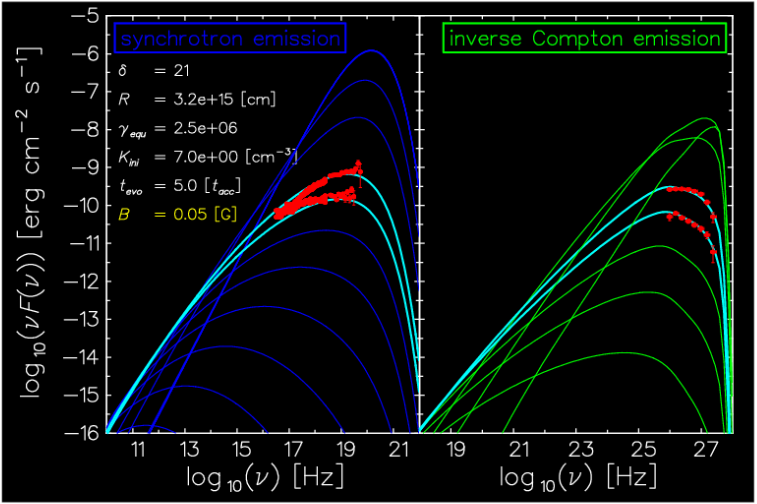
The radiation field energy density



Evolution of the electron spectrum



SSC emission of Mrk 501



obs. - Pian et al. 1998, Djannati–Atai, A. et al 1999, model - Katarzyński et al. 2006

SSC - number of free parameters

- mono-energetic particle population

$$R, \quad B, \quad K_\gamma, \quad \gamma, \quad \delta \quad \rightarrow \quad \boxed{5}$$

- power law particle spectrum

$$R, \quad B, \quad K_1, \quad \gamma_{\rm max}, \quad n, \quad \delta \quad \rightarrow \quad \boxed{6}$$

- broken power law spectrum

$$R, \quad B, \quad K_1, \quad \gamma_{\rm break}, \quad \gamma_{\rm max}, \quad n_1, \quad n_2, \quad \delta \quad \rightarrow \quad \boxed{8}$$

- our model (no escape and injection)

$$R, \quad B, \quad K_{\rm ini}, \quad \gamma_{\rm equ}, \quad t_{\rm acc}, \quad t_{\rm evo}, \quad \delta \quad \rightarrow \quad \boxed{7}$$

where R - source radius, B - magnetic field intensity, K - particle density, γ - particle Lorentz factor, n - spectral index, δ - source Doppler factor, $t_{\rm evo}$ - evolution time

... less than seven parameters?

If for the equilibrium energy

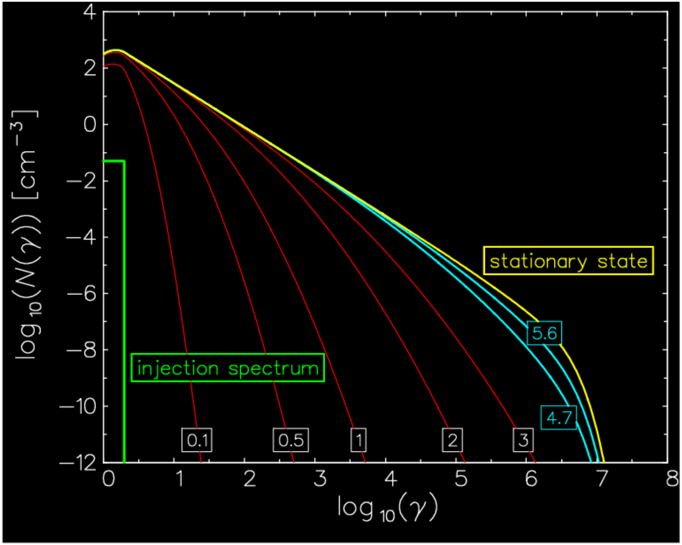
$$U_B \gg U_{\rm rad}(\gamma_{\rm equ})$$

then the value of the magnetic field intensity can be derived from the other model parameters

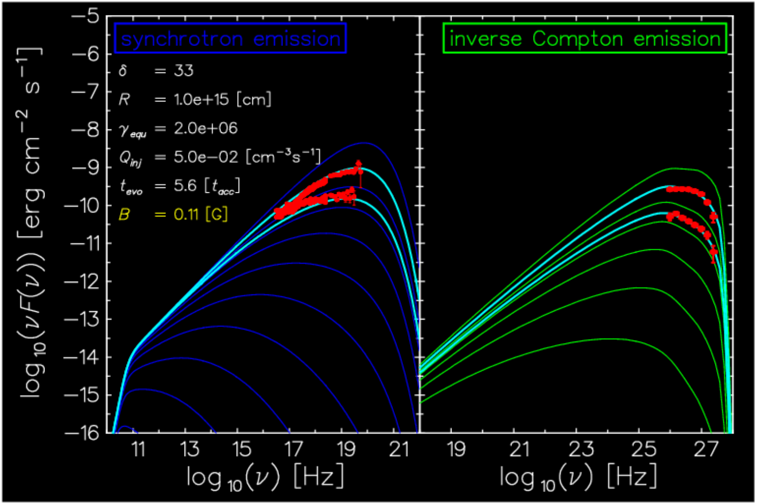
$$B(\gamma_{\rm equ}, t_{\rm acc}) = \sqrt{\frac{6\pi m_e c}{\sigma_{\rm T}} \frac{1}{\gamma_{\rm equ} t_{\rm acc}}} \quad \rightarrow \quad \boxed{7 \rightarrow 6}$$

Moreover, if $t_{\rm acc} \simeq R/c$ then the number of free parameters is reduced to $\boxed{5}$!

Injection & escape scenario



Mrk 501 - injection & escape scenario



obs. - Pian et al. 1998, Djannati–Atai, A. et al 1999, model - Katarzyński et al. 2006

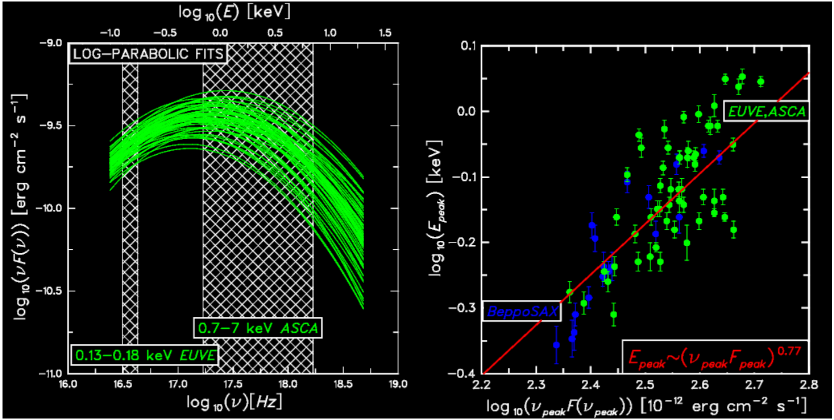
free parameters in the inj/esc scenario

In the injection and escape scenario in principle we have eight free parameters

$$R, \quad B, \quad Q_{\rm inj}, \quad \gamma_{\rm equ}, \quad t_{\rm acc}, \quad t_{\rm esc}, \quad t_{\rm evo}, \quad \delta \quad \longrightarrow \quad \boxed{8}$$

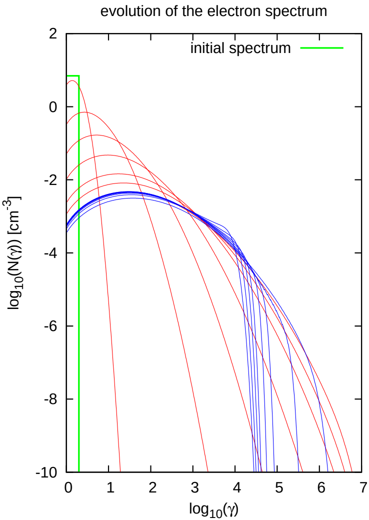
However, we can assume the escape time $t_{\rm esc} \simeq R/c \rightarrow \boxed{7}$.
Moreover, since the slope of the spectrum $n = 1 + \frac{t_{\rm acc}}{2t_{\rm esc}}$, the acceleration time $t_{\rm acc} \simeq t_{\rm esc} \rightarrow \boxed{6}$. The magnetic field intensity can be calculated if $U_B \gg U_{\rm rad}(\gamma_{\rm equ}) \rightarrow \boxed{5}$.
Finally, if we observe the source in the stationary state then the $t_{\rm evo}$ can be eliminated $\rightarrow \boxed{4}$!

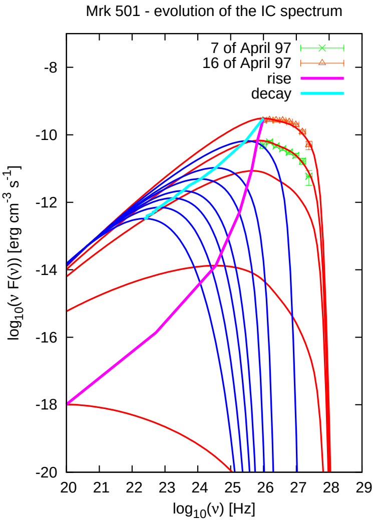
Mrk 421 – synchrotron peak correlation



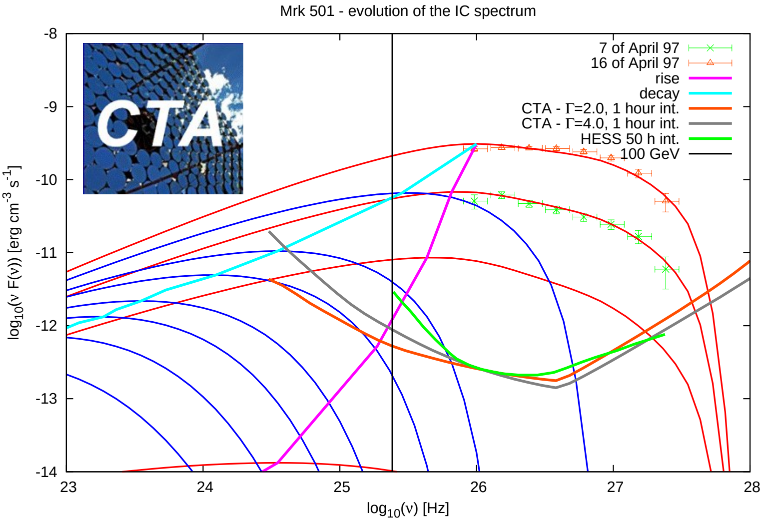
Tanihata et al. 2004

Peak correlation – acceleration scenario

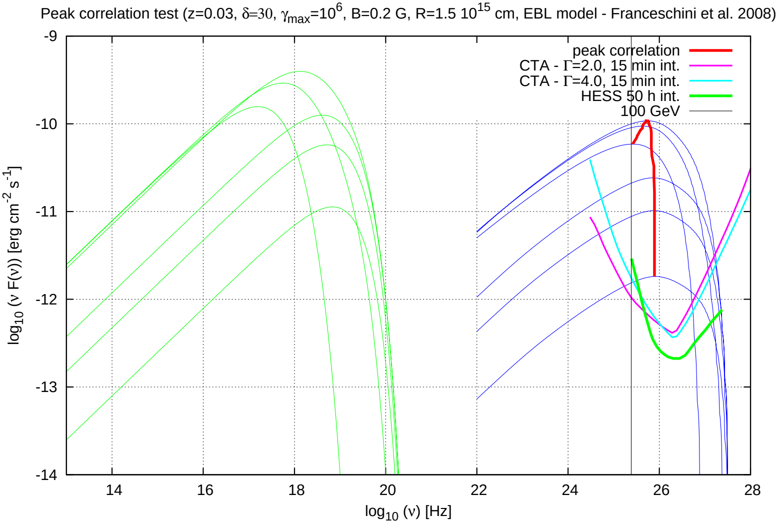




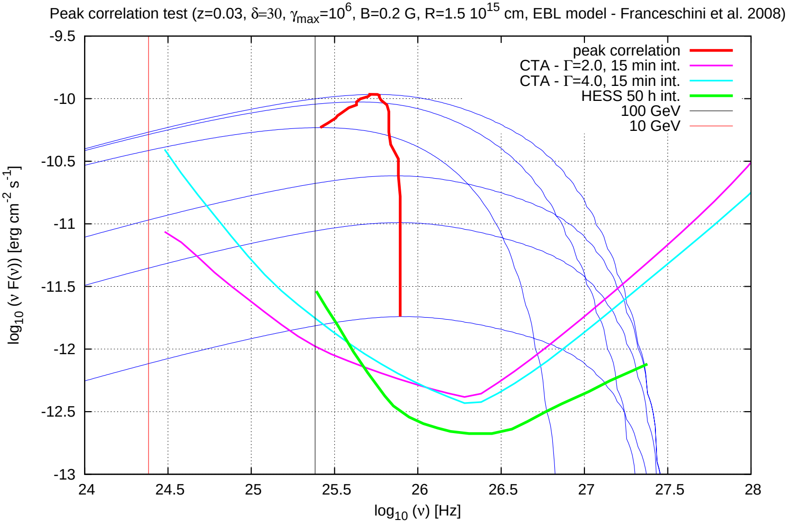
Peak correlation – acceleration scenario



Peak correlation – injection scenario



Peak correlation – injection scenario



Mrk 501 – delay between the TeV light-curves

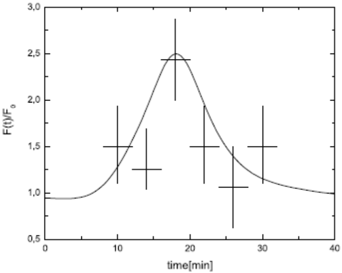


Fig. 2. Time evolution of the flare described in the text in the low (0.15–0.25 TeV) TeV band. Time is as measured by an observer in the lab frame. Observations were taken from Albert et al. (2007).

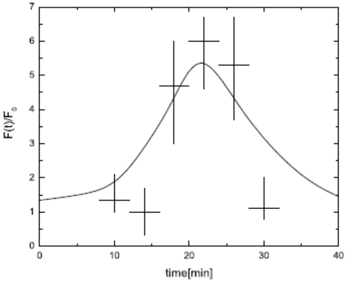


Fig. 3. Time evolution of the flare described in the text in the high (1.2–10 TeV) TeV band. Time is as measured by an observer in the lab frame. Observations were taken from Albert et al. (2007).

obs. - Albert et al. 2007, model - Mastichiadis & Moraitis 2009

Clockwise & anticlockwise loops

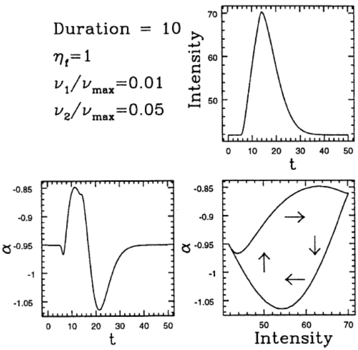


Fig. 3. The intensity and spectral index during the flare described by Eq. (23), as a function of time at low frequency. The loop in the α vs. intensity plot is followed in the clockwise direction.

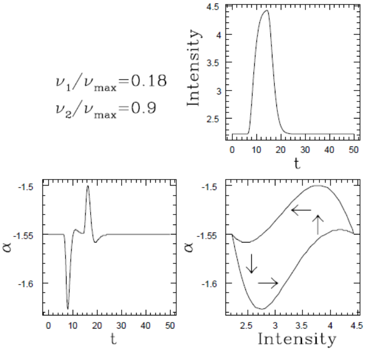


Fig. 4. The intensity and spectral index in the same flare as in Fig. 3 but at high frequency. The loop in the α vs. intensity plot is followed in the anticlockwise direction.

Kirk, Rieger & Mastichiadis 1998

Conclusions

- particle acceleration at a shock wave can be approximated as an injection of the relativistic particles – this is the simplest possible description
- in a more precise approach the acceleration process can be described by the kinetic equation – in our particular model we use the diffusion equation to simulate stochastic nature of the acceleration
- we tested two different approaches: acceleration & cooling only and continuous injection, acceleration, cooling and escape of the particles – in both cases we well reproduce the observed spectra
- future high energy instruments like for example CTA will provide very important details about the acceleration

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