On the connection of radio and γ-ray emission of blazars

Abstract

Blazars have their jet pointing towards us and are known for their emission that covers practically all electromagnetic spectrum frequencies. These sources, in some cases, exhibit a correlation between γ-ray and radio emission, especially during flaring episodes. Adopting the hypothesis that high-energy photon emission by relativistic electrons occurs close to the central black hole, we study the evolution of this population of particles as they move along the jet and lose energy by radiation and adiabatic expansion. In this scenario, γ-rays are produced early on, when the electrons are still very energetic, while radio emission at a later time when the emission region becomes optically thin to synchrotron self-absorption due to expansion. We develop an expanding one-zone code to calculate the emitted spectrum by simultaneously solving the kinetic equations of particles and photons. We will discuss the parameters entering our calculations, like the magnetic field strength, the density of relativistic electrons, etc., in connection to the observational data by applying our results to the case of Mrk421.

Model Setup

The characteristics of our model are:

- An emitting region (a blob of radiative relativistic electrons) which expands with an expanding velocity u_{exp}.
- The blob of plasma is assumed to be spherical with radius $R(t) = R_0 + u_{exp}t$ in its comoving frame (where R_0 is the initial radius of the source) and moves with highly relativistic speed βc, giving it a Lorentz factor $\Gamma = (1-\beta^2)^{-1/2}$. The jet makes an angle to our line of sight θ, thus the relativistic Doppler factor is $\delta = [\Gamma(1-\beta\cos\theta)]^{-1}$.
- The magnetic field has the strength $B = B_0\left(\frac{R_0}{R}\right)^s$, where B_0 is the initial value of the magnetic field and s is a free parameter.
- Relativistic electrons with a power law distribution are injected (Q_e). The electrons luminosity are related to Q_e by $L_e^{inj} = m_e c^2 \int_{\gamma_{min}}^{\gamma_{max}} Q_e(\gamma, t)\gamma d\gamma$ where $Q_e(\gamma, R) = q_e(R(t))\gamma^{-p} = q_{e_0}\left(\frac{R_0}{R(t)}\right)^{\chi}\gamma^{-p}, \quad \gamma_{min} \le \gamma \le \gamma_{max}$, where χ can be positive or negative, and γ_{min}, γ_{max} are, respectively, the minimum and maximum Lorentz factors of the electron distribution..
- The characteristic time scale of the problem is the initial crossing time of the source, $t_{cross} = \frac{R_0}{c}$.

Numerical Approach: We developed a numerical code, based on [3] in order to calculate the temporal evolution of the electrons and photons distribution function [1]. This code solves two integro-differential equations, each describing the losses/sinks ($\mathcal{L}$) and injection of relativistic electrons (Q_e) and photons in the emitting region. The kinetic equation of electrons reads:

$$\frac{\partial N(\gamma, t)}{\partial t} + \sum \mathcal{L}_i N(\gamma, t) = Q_e(\gamma,\ t),$$

$$\sum \mathcal{L}_i = \frac{\partial}{\partial \gamma}\left[\left(A_{syn}(\gamma,\ t) + A_{ICS}(\gamma,\ t) + A_{ad}(\gamma,\ t)\right)\right]$$

where the terms A_{syn}, A_{ICS}, A_{ad} are the loss rates for synchrotron emission, inverse Compton scattering, and adiabatic expansion respectively.

The role of synchrotron self-absorption: The frequency below which the synchrotron radiation is absorbed can be derived by the condition $\alpha_{\nu_{ssa}} R(t) \sim 1$ where $\alpha_{\nu_{ssa}}(t)$ is the absorption coefficient (e.g. [4]).

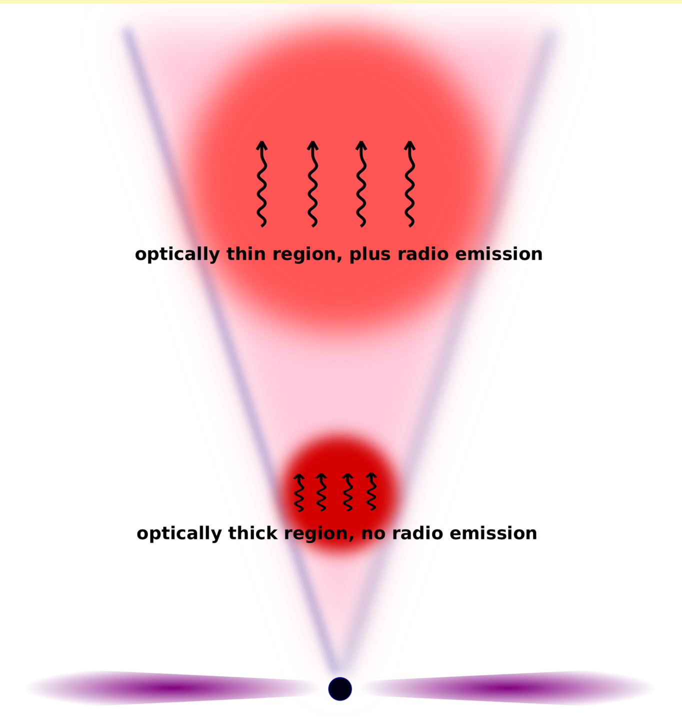


Figure: A sketch of our model. High energy emission is produced close to the central engine; on the other hand, radio frequencies are absorbed. The source becomes optically thin at further distances.

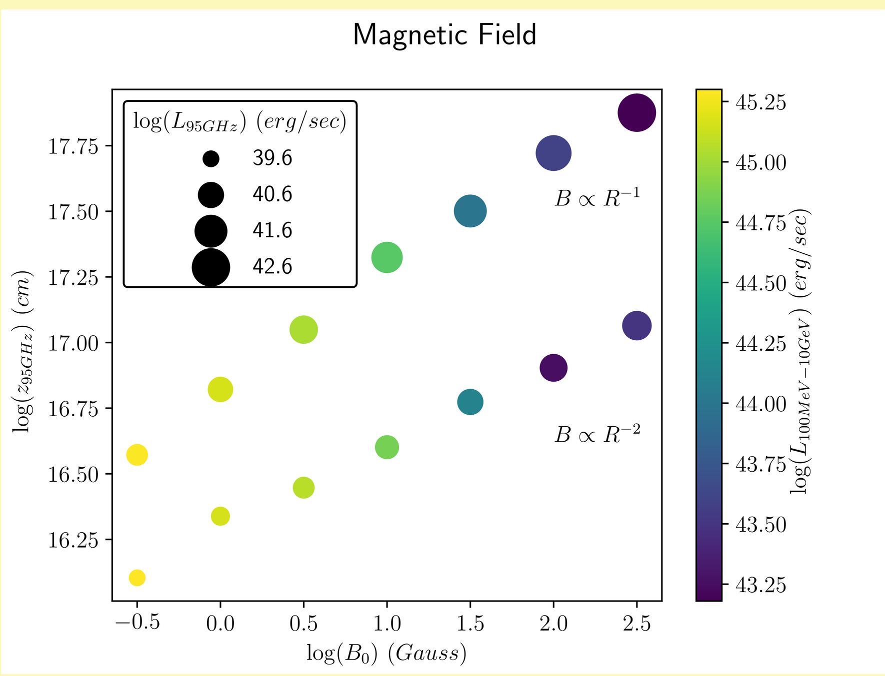


Figure: The dependence on initial magnetic field value of the distance where the radio frequencies escape. The figure depicts two different radius profiles. Also, the γ-ray (at the base of the jet) and radio luminosity (at the distance where the source is optically thin) are represented. $R_0 = 10^{15}$ cm, $L_{e_0}^{inj} = 10^{42}$ erg s^{-1}, $u_{exp} = 0.1$ c, $\gamma_{min} = 1$, $\gamma_{max} = 10^6$, $p = 2$, $\delta = 10$ and $z_{init} = 0.01$ pc.

Steady State Emission

1. We assume that blobs with the same initial properties are continuously created at a distance z_0 from the central engine. This is equivalent to a conical flow with a half-opening angle $\phi = \arctan(R_0/z_0)$. The distance z traveled by a blob since its "birth", as measured in the black hole's rest frame, is related to its radius R as: $z(t) = z_0 + \beta c(R(t) - R_0)/\Gamma u_{exp}$.
2. We integrate along the line of sight the SED in order to reproduce the total steady-state spectrum of the source which is observed.
3. We compare our results with the observational data of the source Mrk421.

Flaring Episodes

We assume a re-acceleration episode in a distance z from the central engine. The injected electrons distribution has the form:

$$Q_e(\gamma, R) = q_e(R(t))\gamma^{-p}\left(1 + \frac{\alpha w^2}{4(t-t_0)^2 + w^2}\right) = q_{e_0}\left(\frac{R_0}{R(t)}\right)^{\chi}\gamma^{-p}\left(1 + \frac{\alpha w^2}{4(t-t_0)^2 + w^2}\right),$$

where α is the value at maximum, w the width of the injection and t_0 the time when the maximum is injected.

These flaring episodes - depending on the set of parameters- reproduce symmetrical and extended flares.

Application to Mrk421

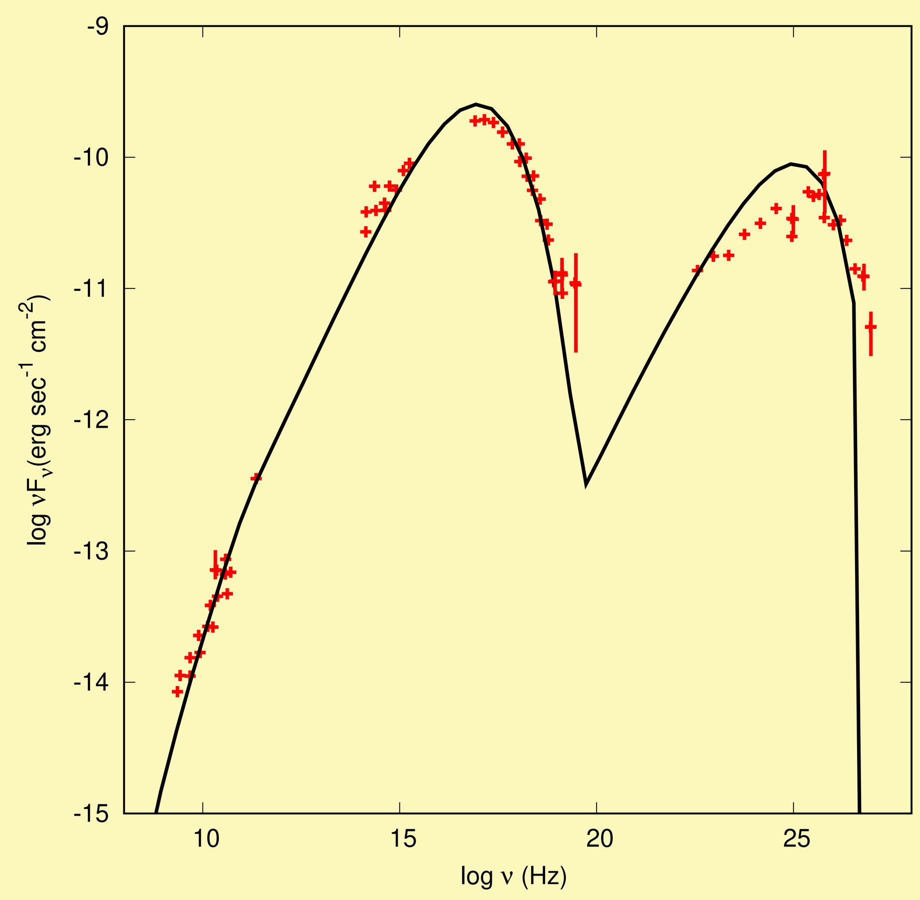
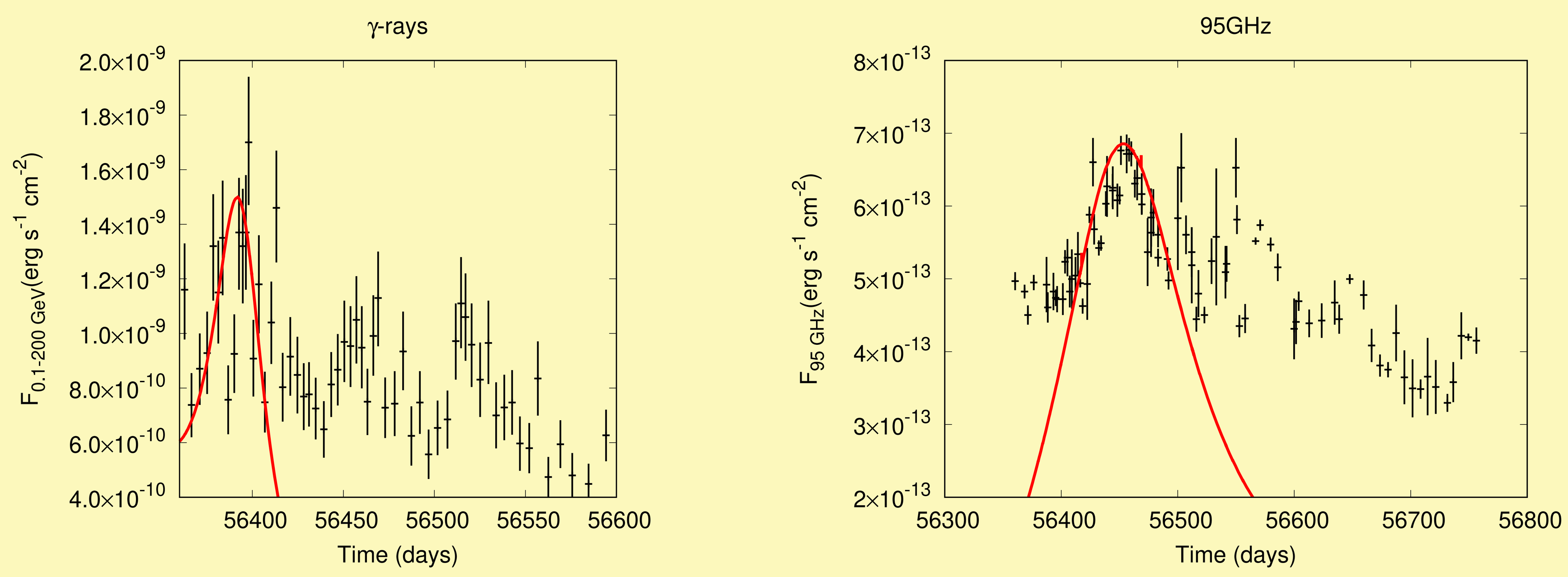


Figure: Steady-state SED of a fiducial BL Lac source (thick black line), computed by superimposing the emission of 10^3 blobs that are produced continuously at distance $z_0 = 10^{-2}$ pc from the central engine. All blobs are initialized with the same parameters: $B_0 = 0.3$ G, $R_0 = 10^{16}$ cm, $L_{e_0}^{inj} = 3 \times 10^{41}$ erg s^{-1}, $u_{exp} = 0.2$ c, $\gamma_{min} = 1$, $\gamma_{max} = 10^6$, $p = 2$ $\delta = 10$. The magnetic field and electron injection luminosity decrease linearly with radius ($s, \chi = 1$).



Modeling of Mrk 421 2013 flare. Observational data are presented at [2]. The parameter set that we use in this modelling are: $R_0 = 10^{16.6}$ cm,$B_0 = 1.25$ G, $L_{e_0}^{inj} = 10^{43.2}$ erg s^{-1}, $u_{exp} = 0.05$ c, $\gamma_{min} = 1$, $\gamma_{max} = 10^{5.1}$, $p = 2$, $\delta = 10$ and $z_{init} = 0.01$. Magnetic field decreases as $B \propto R^{-1}$ and electrons luminosity as $L_{e_0}^{inj} \propto R^{-2}$. For the γ-ray flare we used a pulse which was injected at $t_0 = 40\ t_{cr_0}$, with a width $w = 23\ t_{cr_0}$ and its peak is 60 times larger than the blob's luminosity at peak's time.

Conclusions

- Development of a new one-zone expanding numerical leptonic code.
- Prediction of the localization of radio emission depending on the basic physical quantities of the source.
- Flares in radio and γ-rays may be produced by re-acceleration of electrons at a large distance from the central engine.
- Close to the central engine radio flares could not be produced.

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