Acta Physica Polonica B Proceedings Supplement **15**, 3-A12 (2022)

AN EXPANDING MODEL TO EXPLAIN BLAZARS EMISSION*

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Received 15 April 2022, accepted 16 May 2022,

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, radio emission is produced 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, such as the magnetic field strength, the density of relativistic electrons, *etc.*, in connection to the observational data by applying our results to the case of blazars.

DOI:10.5506/APhysPolBSupp.15.3-A12

1. Introduction

Active Galactic Nuclei (AGN) are compact regions at the center of galaxies, where supermassive black holes exist with masses between 10^6–10^{10} solar

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[*] Presented at the 28th Cracow Epiphany Conference on *Recent Advances in Astroparticle Physics*, Cracow, Poland, 10–14 January, 2022.

masses. These regions convert efficiently their dynamic energy into radiation through mass accretion. The photons that are produced cover essentially the whole of the electromagnetic spectrum, from radio to γ rays.

A particular subcategory of AGN are blazars, which have strong relativistic jets pointing toward us. Blazars exhibit some unique features, such as the large amount of energy that they emit, the rapid changes in luminosity, and the non-thermal emission with a characteristic signature in γ rays. Their spectrum can only be explained by a population of charged ultra-relativistic particles, making these sources cosmic accelerators. They are divided into two main subcategories: the Flat Spectrum Radio Quasars (FSRQs) and BL Lac objects. The former have predominantly strong emission lines in their spectrum and larger bolometric luminosity comparing to the latter. Taking into account the theoretical models proposed so far, we could say that these are mainly based on the assumption that the particles accelerate at high energies within a region located inside the jet [1]. In addition, radiation is emitted due to the accelerated charged particles interactions with the magnetic fields and ambient photon fields existing in the acceleration region. Models that propose electrons as the radiating particles are called leptonic and can adequately explain the observed spectra. However, this does not rule out relativistic protons within these sources, thus making necessary the study of models called leptohadronic models that consider both types of particles. The emitted spectrum of the particles is calculated from the radiative transfer equations using high-energy processes. In astrophysical environments, where high-energy densities prevail in both photon and magnetic fields, radiation production and propagation problems are particularly complex. Along these lines, an innovative numerical approach to the problem was introduced in [2] and later in [3]. In the above articles, all the relevant physical interactions between relativistic protons, electrons, and photons were presented and the kinetic equations were constructed in a self-consistent way. The system consists of three coupled integro-differential equations which describe the temporal and spectrum evolution of the particles. In this work, we will focus on the leptonic scenario and how it can give answers to open questions related to the localization of the emission and rapid variability of blazars.

1.1. Localization of radio emission

In particular, the localization of radio emission of blazars is an open question [4]. It is well known that low-frequency radio photons are absorbed by relativistic electrons, creating a characteristic "break" of the spectrum at the so-called synchrotron self-absorption frequency [5]. However, blazars show an emission in radio frequencies, which cannot be explained when one models this emission alongside with their emission in other frequencies. Therefore, one simple explanation could be that radio photons are emitted from a different area further down the jet.

We consider the above problem by extending the numerical code mentioned earlier to include the source's adiabatic expansion [6, 7]. In this way, we reproduce the temporal evolution of high-energy electrons as they propagate along the jet. Thus, the total spectrum of these sources comes from the superposition of the different spectra of blobs, which are emitted at different positions inside the jet. The flow is essentially converted to a continuous conical jet whose behavior is determined by the boundary conditions at the base of the jet and its dynamics. Finally, comparing with the observations, we can identify the localization of radio emission, the characteristics, and the radiating relativistic electron characteristics.

1.2. Rapid variability

Blazars show flares in the gamma rays, which sometimes can be as short as a few minutes. In addition to that, in several cases, there are time delays between high-energy (γ rays) and low-energy (radio) emission [8]. According to some theoretical models, [9], flares can be associated with sudden injection of electrons inside the acceleration region, and through differential cooling and an adiabatic expansion γ rays and radio could show a time delay [7]. By comparing the theoretically produced results with the observational data, we can draw useful conclusions about the causes of this rapid variability.

2. Expanding model

The frequency below which the synchrotron radiation is absorbed can be derived by the condition $\alpha_{\nu_{\rm ssa}} R(t) \sim 1$, where $\alpha_{\nu_{\rm ssa}}(t)$ is the absorption coefficient (*e.g.* [10]) and $\nu_{\rm ssa}$ is the synchrotron self-absorption frequency, which is a function of blob radius through its dependence on the magnetic field and electron number density. A blob at small distances from the jet base is optically thick to synchrotron radiation, but it becomes optically thin as it expands and moves to further distances. In order to treat this physical problem, we use the numerical code based on [2] to calculate the temporal evolution of the electrons and photons distribution function in the case of an expanding source [6, 7]. This code solves two integro-differential equations, each describing the losses ($\mathcal{L}$) and injection of relativistic electrons (Q_e) and photons in the emitting region. The kinetic equation of electrons reads

$$\frac{\partial N(\gamma,t)}{\partial t} + \sum \mathcal{L}_i N(\gamma,t) = Q_e(\gamma,\ t)\,, \tag{1}$$

$$\sum \mathcal{L}_i = \frac{\partial}{\partial \gamma}\left[(A_{\rm syn}(\gamma,\ t) + A_{\rm ICS}(\gamma,\ t) + A_{\rm ad}(\gamma,\ t))\right]\,, \tag{2}$$

where the terms $A_{\rm syn}$, $A_{\rm ICS}$, $A_{\rm ad}$ are the loss rates for synchrotron emission, inverse Compton scattering, and adiabatic expansion, respectively. We assume that electrons are injected into the source with a power-law distribution given by

$$Q_e = k_e \gamma^{-p} \qquad \text{for} \qquad \gamma_{\rm min} \leq \gamma \leq \gamma_{\rm max}\,, \tag{3}$$

where the electrons luminosity $L_e^{\rm inj} = m_e c^2 \int_{\gamma_{\rm min}}^{\gamma_{\rm max}} Q_e(\gamma)\gamma\,{\rm d}\gamma = \eta_e P_{\rm acc}$, with η_e being a proportionality constant ($\eta_e < 1$). Here, $P_{\rm acc} = \dot{m}\mathcal{M}L_{\rm Edd}$, with $\dot{m}$ the mass accretion rate normalized to the Eddington one and $\mathcal{M} = M_{\rm BH}/M_\odot$, where $M_{\rm BH}$ is the mass of the black hole. The electron distribution is characterized by $\gamma_{\rm min}$ and $\gamma_{\rm max}$ (the minimum and maximum electrons Lorentz factors), p the index of the electron distribution, all input parameters required for the calculation of the spectrum are scaled with $\dot{m}$ and $\mathcal{M}$. Thus, one can write [11]: $U_{\rm B} \propto \eta_{\rm b}\dot{m}\mathcal{M}^{-1}$, $L_e^{\rm inj} \propto \eta_e\dot{m}\mathcal{M}$, where $\eta_{\rm b}$ is a proportionality constant of the accreting mass into radiation.

3. Steady-state emission

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

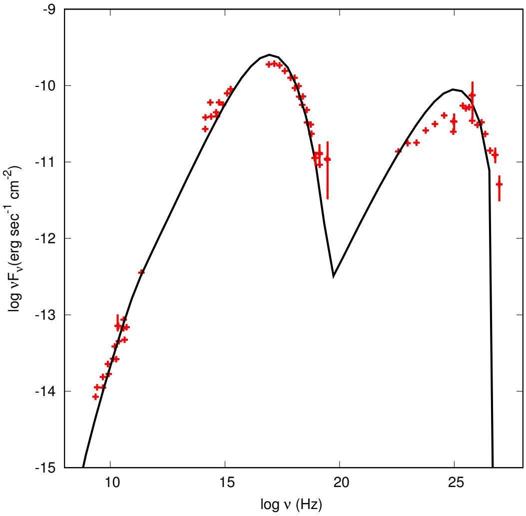

Fig. 1. Steady-state SED of a fiducial BL Lac source (thick black line), computed by superimposing the emission of 10^3 blobs that are produced continuously at distance $z_0 = 10^{-2}$ pc from the central engine. All blobs are initialized with the same parameters: $B_0 = 0.3$ G, $R_0 = 10^{16}$ cm, $L_{e0}^{\rm inj} = 3 \times 10^{41}$ erg s^{-1}, $u_{\rm exp} = 0.2$ c, $\gamma_{\rm min} = 1$, $\gamma_{\rm max} = 10^6$, $p = 2$ $\delta = 10$. The magnetic field and electron injection luminosity decrease linearly with radius ($s, \chi = 1$).

traveled by a blob since its "birth", as measured in the black hole's rest frame, is related to its radius R as: $z(t) = z_0 + \beta c(R(t) - R_0)/\mathit{\Gamma} u_{\rm exp}$. Furthermore, we integrate along the line of sight the SED in order to reproduce the total steady-state spectrum of the source which is observed. Finally, we compare our results with the observational data of the source Mrk421, figure 1. Furthermore, in figure 2, we investigate the role of the accretion mass rate and the expansion velocity to reproduce the sequence of BL Lac objects.

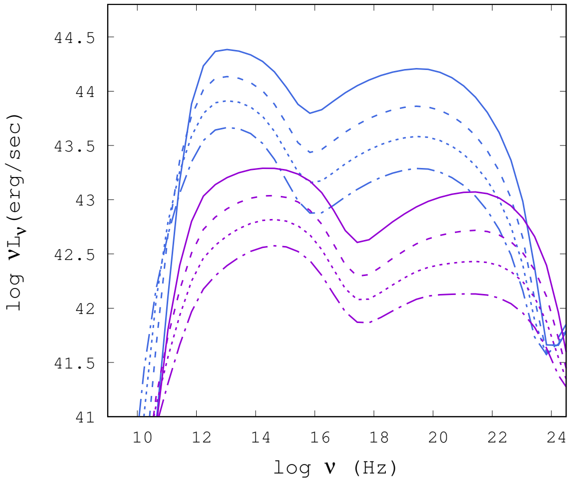

Fig. 2. (Color online) Spectra corresponding to BL Lac objects for two different mass accretion rates. The family of spectra shown in blue (gray) refers to a larger $\dot{m}$ while the different curves, respectively, refer to different source expansion velocities, in order from top to bottom $u_{\rm exp} = 0.010,\ 0.025,\ 0.050,\ 0.100$. Respectively for the curves with purple (black) color that correspond to a lower accretion mass rate. The other parameters are in Table 1.

Table 1. The values of the parameters for different values of the mass accretion rate in the case where $\mathcal{M} = 10^8$. All parameters are on a logarithmic scale. The source is at a distance of $z = 0.01$ pc and we calculate the total range produced up to the distance $z_{\rm final} = 10$ pc. The initial radius of the source is $R_0 = 10^{15}$ cm, while the index of the power-law electron distribution is $p = 2$. The bulk Lorentz factor is $\mathit{\Gamma} = 30$ and the Doppler factor is $\delta = 15$. The magnetic field and the brightness of the electrons decrease linearly with the radius.

B_0(G)	L_{e_0} $\left[\frac{\rm erg}{\rm sec}\right]$	$\gamma_{\rm max}$	Blazar class
1.5	43.5	4	LBL
1.0	42.5	5	HBL

4. Flares

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

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

for $\gamma_{\min} \leq \gamma \leq \gamma_{\max}$, where α is the value at maximum, w the width of the injection, and t_0 the time when the maximum injection. These flaring episodes — depending on the set of parameters — reproduce symmetrical and extended flares. This is related to a strong cooling due to radiation losses or adiabatic losses, respectively. In other words, the position, where the particle re-acceleration episode happens, plays a key role in the photon production. If the episode occurred at the optically thick region, radio photons would be absorbed. In figure 3, we reproduce two flaring episodes in the optically thin region of the source 0827+243 by assuming Lorentzian forms for the electron-energy distribution.

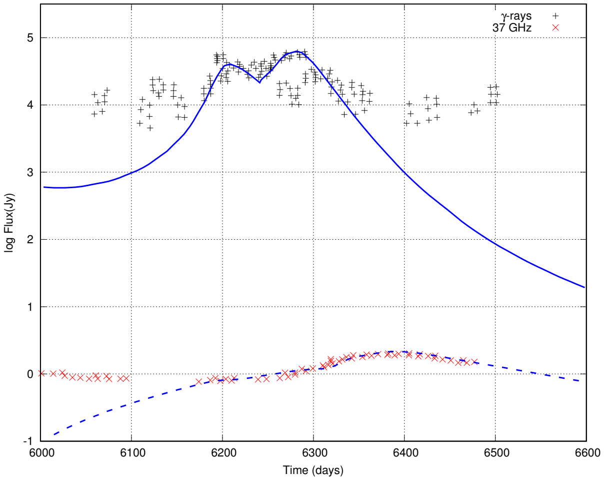

Fig. 3. A test case for modeling the flares of the quasar 0827+243 (data from [12]). The continuous line refers to γ rays (0.1–200 GeV) and dashed to radio photons (37 GHz). It is reproduced by two flaring episodes assuming the scenario of Lorentzian distributions.

5. Discussion — conclusions

This paper applies the one-zone expanding model to blazars emission. Here, we self-consistently solve the kinetic equations of electrons and photons at each source radius or, equivalently, at every distance from the central engine. In Fig. 1, we present the modeling of Mrk421 steady-state emission, assuming a conical jet that is produced by the superposition of 10^3 spherical blobs which are spread throughout the jet length. As a zero-order approximation, we keep the initial values of magnetic field strength and electron power constant in time due to a fixed accretion mass rate. The distance where radio emission becomes optically thin is approximately 1 pc. Figure 2 presents the SEDs for BL Lac objects depending on the mass accretion rate, as it has been shown in [11, 13] for the non-expanding case. The peak of the frequencies and the luminosities of the two components are similar to those of intermediate and high synchrotron peaked blazars and the same can be said for the γ-rays photon indices. For increasing u_{exp} values, the magnetic field strength decreases faster and the components' peaks shift to lower frequencies. At the same time, the luminosity decreases due to the dependence of the magnetic field and electrons power on the distance of the blob. FSRQs should have similar behavior, but in that case, external photon fields must be considered. In Fig. 3, two flaring episodes are presented by assuming a re-acceleration particle episode; the method is described in [7]. The episodes might be related to a non-constant mass accretion rate. Detecting the correlation between γ rays and radio waves could indicate that the emission is produced in an optically thin area, where the adiabatic losses may play an important role.

To sum up, the basic conclusions of the present research are:

(a) the development of a new one-zone expanding numerical leptonic code,

(b) the localization of radio emission depending on the basic physical quantities of the source, and

(c) the connection between radio and γ-ray flares which are produced by re-acceleration of electrons at a large distance from the central engine.

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