Magnetization of jets in luminous blazars

Mateusz Janiak\textsuperscript{1}, Marek Sikora\textsuperscript{1}, and Rafał Moderski\textsuperscript{1}

ABSTRACT

Luminosities of many powerful blazars are strongly dominated by $\gamma$-rays which most likely result from Comptonization of radiation produced outside a jet. This observation sets certain constraints on composition and energetics of the jet as well as the surrounding quasar environment. We study the dependence of a Compton dominance on a jet magnetization (the magnetic-to-matter energy flux) and on the location of the 'blazar zone'. Calculations are performed for two geometries of broad-emission-line and hot-dust regions: spherical and planar. The jet magnetization corresponding to the large observed Compton dominance is found to be $\sim 0.1(\theta_j \Gamma)^2$ for spherical geometries and $\sim 0.01(\theta_j \Gamma)^2$ for planar geometries, where $\theta_j$ is the jet half-opening angle and $\Gamma$ is the jet Lorentz factor. This implies that jets in luminous blazars are matter dominated and that this domination is particularly strong for the flattened geometry of external radiation sources.

Subject headings: quasars: jets – radiation mechanisms: non-thermal – acceleration of particles

1. Introduction

As indicated by CGRO/EGRET (von Montigny et al. 1995) and confirmed by Fermi/LAT (Abdo et al. 2010; Ackermann et al. 2011), apparent luminosities of blazars associated with flat spectrum radio quasars (FSRQ) are often dominated by $\gamma$-rays. For most of them the ratio of the $\gamma$-ray luminosity to synchrotron luminosity is larger than 4 and in many cases exceeds 10 (see Giommi et al. 2012, Fig. 22). A dense radiative environment in the quasar nuclei strongly favours the external-radiation-Compton (ERC) mechanism of $\gamma$-ray production (see Sikora et al. 2009, and refs. therein). In such a case with the assumption of the 'one-zone' model the $\gamma$-to-synchrotron luminosity ratio can be approximated by the ratio of

\textsuperscript{1}Nicolaus Copernicus Astronomical Center, Bartycka 18, 00-716 Warsaw, Poland; mjaniak@camk.edu.pl, sikora@camk.edu.pl
the external radiation energy density, \( u'_\text{ext} \), to the internal magnetic energy density, \( u'_B \), both as measured in the jet co-moving frame. Hence, combining knowledge about external radiation fields, kinematics of a jet, and observationally determined Compton dominance one may estimate intensity of the magnetic field in the blazar zone and then the flux of the magnetic energy \( L_B \). Comparison of \( L_B \) with the total jet energy flux, \( L_j \sim L_\gamma/(\eta_{\text{rad}}\eta_e\eta_{\text{diss}}\Gamma^2) \) can then be used to determine the sigma parameter, \( \sigma \), defined to be the ratio of the magnetic energy flux to the matter energy flux, i.e. \( \sigma \equiv L_B/L_{\text{kin}} = (L_B/L_j)/(1 - (L_B/L_j)) \), where \( \eta_{\text{diss}} \) is the fraction of \( L_j \) dissipated in the blazar zone, \( \eta_e \) is the fraction of dissipated energy channeled to accelerate electrons, and \( \eta_{\text{rad}} \) is the average radiative efficiency of relativistic electrons (Sikora et al. 2013).

Studies of \( \sigma \) parameter are important not only for better understanding of dynamical structure and evolution of relativistic jets, but also because its value determines the dominant particle acceleration mechanism (shock vs. reconnection) and its efficiency and, therefore, should be performed in a more systematic and complete manner than so far. In particular, one should take into account such uncertainties as location of the blazar zone and geometry of the external radiation fields. In both cases uncertainties are still very large. The blazar zone deduced by some models is located at \( \sim 300R_g \) (see Stern & Poutanen 2011), while in others even up to thousands times farther (see Marscher & Jorstad 2010). Also the geometry of the broad-line region (BLR) and of hot-dust region (HDR) is often considered to be spherical and not stratified, while in reality it may be very flat and significantly radially extended (for BLR see Vestergaard et al. 2000; Decarli et al. 2008; and Decarli et al. 2011; for HDR, e.g. Wilkes et al. 2013; Roseboom et al. 2013). In this paper we present results of such studies by mapping theoretical blazar spectral features as a function of a distance, external photon sources geometry, and jet magnetization and comparing them with observations.

Our theoretical models of broad band spectra are constructed using knowledge of typical parameters of radio-loud quasars: BH masses, Eddington ratios, and jet powers. We assume strong coupling between protons and electrons as indicated by particle-in-cell (PIC) simulations (see Sironi & Spitkovsky 2011). Detailed model assumptions are specified and discussed in \( \S 2 \). Results of our modeling of blazar spectra and their features (bolometric apparent luminosities, locations of the spectral peaks, Compton dominance, external photon sources energy densities) dependence on a distance from the BH for different \( \sigma \) values and different geometries of external radiation fields are presented in \( \S 3 \). They are discussed and summarized in \( \S 4 \).
2. Model Assumptions

2.1. Dissipation region

The jet is assumed to propagate with a constant bulk Lorentz factor $\Gamma$ and to diverge conically with a half opening angle $\theta_{\text{jet}} = 1/\Gamma$. Energy dissipation and particle acceleration are assumed to take place within a distance range $r_1 - r_0 = r_0$ and proceed in the steady-state manner (Sikora et al. 2013). Radiation production is followed up to distance $r_2 = 10r_1$. The emitting jet volume is divided into $s$ cells, each with the same radial size $\delta r = (r_2 - r_0)/s$. Assuming uniformity of matter, magnetic fields and external photon fields across the jet and within the cell thickness $\delta r$, the emitting jet volume is approximated as a sequence of 'point sources' (the real cell emission volume is used only to compute density of the synchrotron radiation needed to calculate the synchrotron self-Compton (SSC) luminosity). Jet radiation spectra are computed for different $r_0$ and presented as a function of the parameter $r = 1.5r_0$.

2.2. Electron acceleration and cooling

We follow evolution of electron energy distribution in the region of interest by solving the kinetic equation for relativistic electrons (Moderski et al. 2003) which can be presented in the form

$$\frac{\partial N_{\gamma,i}(r)}{\partial r} = -\frac{\partial}{\partial \gamma} \left( N_{\gamma,i}(r) \frac{d\gamma}{dr} \right) + \frac{Q_{\gamma,i}(r)}{c\beta \Gamma},$$

(1)

where $N_{\gamma,i}$ is the number of electrons per energy and cell volume, $\beta = \sqrt{\Gamma^2 - 1}/\Gamma$, $d\gamma/dr = (d\gamma/d\gamma')/(\beta c\Gamma)$, $d\gamma/d\gamma'$ are the electron energy loss rates as measured in the jet co-moving frame, and $Q_{\gamma,i}(r)$ is the electron injection function assumed to take the form

$$Q_{\gamma,i}(r) = K_if(\gamma),$$

(2)

where

$$f(\gamma) = \begin{cases} \gamma^{p_1-p_2}\gamma^{p_1} & \text{for } \gamma_{\text{min}} \leq \gamma \leq \gamma_b, \\ \gamma^{-p_2} & \text{for } \gamma_b \leq \gamma \leq \gamma_{\text{max}}. \end{cases}$$

(3)

Assuming that each electron is involved in the acceleration process, one can relate normalization of the injection function, $K_i$, to the jet power using the following formula

$$K_i = \left( \frac{\delta r}{r_1 - r_0} \right) \left( \frac{\eta_e \eta_{\text{diss}} L_{1,0}}{(\bar{\gamma}_{\text{inj}} - 1)m_e c^2 \int_{\gamma_{\text{min}}}^{\gamma_{\text{max}}} f(\gamma) d\gamma} \right),$$

(4)

where

$$\bar{\gamma}_{\text{inj}} \equiv \int_{\gamma_{\text{min}}}^{\gamma_{\text{max}}} \gamma f(\gamma) d\gamma / \int_{\gamma_{\text{min}}}^{\gamma_{\text{max}}} f(\gamma) d\gamma$$

(5)
is the average electron energy Lorentz factor and $L_{j,0}$ is the total jet power prior to the dissipation region. Equating this to the expression for an average injected electron energy (Sikora et al. 2013)

$$\tilde{\gamma}_{\text{inj}} = 1 + \frac{m_p/m_e}{n_e/n_p} \frac{\eta \eta_{\text{diss}}}{(1 - \eta_{\text{diss}})(1 - 1/\Gamma)(1 + \sigma)}$$

(6)
gives the value of break energy in the electron spectrum $\gamma_b$, where $m_e$ and $m_p$ are the electron and proton masses, respectively, and $n_e/n_p$ is the pair content. For $p_1 < 1$ (as expected in case of strong coupling between electrons with protons heated in the dissipation zone), $p_2 > 2$ (as indicated by Fermi/LAT observations), and $\gamma_{\text{min}} \ll \gamma_b \ll \gamma_{\text{max}}$, $\gamma_b$ can be found to be of the order of $\tilde{\gamma}_{\text{inj}}$.

Synchrotron, SSC and adiabatic electron energy loss rates are calculated using procedure presented by Moderski et al. (2003), but with energy density of synchrotron radiation given now by formula

$$u'_{\text{syn},i} = \frac{L'_{\text{syn},i}}{2\pi R \delta rc \Gamma},$$

(7)

where $R = r \theta_i$. The ERC electron losses are computed using approximate formula (Moderski et al. 2005)

$$\left| \frac{d\gamma}{dt} \right|_{\text{ERC}} = \frac{4\sigma_T}{3m_e c^2} \frac{(\beta \delta \gamma) u'_{\text{ext}}}{(1 + b)^{3/2}},$$

(8)

where $b = 4 \gamma \hbar \nu'_{\text{ext}}/m_e c^2$. For spherical geometry of external sources $\nu'_{\text{ext}} = \Gamma \nu_{\text{ext}}$ and for planar geometry $\nu'_{\text{ext}} = \Gamma (1 - \beta \cos \theta_m) \nu_{\text{ext}}$, where $\nu_{\text{ext}}$ and $\nu'_{\text{ext}}$ are the characteristic external photon frequencies in the external and jet co-moving frames, respectively and $\theta_m$ is the angle from which contribution to the energy density in the jet co-moving frame is maximal. Radiation energy densities, $u'_{\text{ext}}$, of external spherical sources are calculated using approximate formulas given in Appendix A, and of planar sources using equations presented by Sikora et al. (2013) in Appendix A.1.

### 2.3. Radiation

In the jet co-moving frame radiation produced within an i-th cell is

$$\left( \frac{\partial L'_{\nu'}}{\partial \Omega'} \right)_i = \int \left( \frac{\partial P'_{\nu'}(\gamma)}{\partial \Omega'} \right)_i N_{\gamma,i} d\gamma,$$

(9)

where the single electron radiative power, $\partial P'_{\nu'}(\gamma)/\partial \Omega'$, is superposed from synchrotron, SSC, and ERC components, the latter consisting of radiation from the accretion disk, from broad
emission region, and from hot dust. Total apparent luminosity is then a sum of radiation from $s$ cells
\[ \nu L_{\text{app,}\nu} = 4\pi \left( \nu \frac{\partial L_{\nu}}{\partial \Omega} \right) = 4\pi \frac{D^2}{\Gamma} \left( \nu \frac{\partial L'_{\nu'}}{\partial \Omega'} \right), \]

where
\[ \frac{\partial L'_{\nu'}}{\partial \Omega'} = \sum_{i=1}^{s} \left( \frac{\partial L'_{\nu'}}{\partial \Omega'} \right)_i, \]
\[ D = \left[ \Gamma(1 - \beta \cos \theta_{\text{obs}}) \right]^{-1}. \]

The synchrotron and SSC luminosities are calculated using procedure presented in Moderski et al. (2003). The ERC luminosities are computed using equations presented in the Appendix B.

### 3. Model parameters

We compute theoretical blazar spectra as a function of the distance from the central black hole $r$, for three different jet magnetization values: $\sigma = 1.0$, 0.1, and 0.01 and for two geometries of external photon sources. We cover four distance decades, from $10^{16}$ cm up to $10^{20}$ cm. We assume a central black hole mass $M_{\text{BH}} = 10^9 M_\odot$, accretion rate $\dot{M} = 3L_{\text{Edd}}/c^2$ and accretion disk radiative efficiency $\eta_d \equiv L_d/\dot{M}c^2 = 0.1$ which gives a total accretion disk luminosity $L_d \approx 4 \times 10^{46}$ erg s$^{-1}$. With such value sublimation radius $r_{\text{sub}} \approx 1$ pc (see Eq. A3). Following the results of numerical simulations of magnetically-arrested disks (McKinney et al. 2012) and noticing observed energetics of jets in radio-loud quasars (see Sikora & Begelman 2013, and refs. therein) we set the jet production efficiency $\eta_j \equiv L_j/\dot{M}c^2 = 1$ which leads to $L_{j,0} \approx 2 \times 10^{47}$ erg s$^{-1}$.

Total efficiency of energy dissipation $\eta_{\text{diss}}$ must be high because of high observed $\gamma$-ray luminosities in FSRQs but should not exceed $\sim 0.5$ as a substantial part of the jet energy needs to be transported to radio lobes of FRII radio sources associated with radio-loud quasars. We set $\eta_{\text{diss}} = 0.3$. We use $\Gamma = 15$ (Hovatta et al. 2009) and the jet opening angle $\theta_j = 1/\Gamma$. Noting the indicated by particle-in cell (PIC) simulations of shocks the strong coupling between electrons and protons (Sironi & Spitkovsky 2011) we assume that dissipated energy is equally distributed between these particles by setting $\eta_h = 0.5$.

Injected electron energy spectrum is assumed to be broken power law, with spectral indices $p_1 = -1$ for $\gamma \leq \gamma_h$ and $p_2 = 2.5$ for $\gamma > \gamma_h$. The choice of very hard low-energy injection function is dictated by mentioned earlier energetical coupling between electrons and protons, while much steeper high-energy portion of the electron injection function is
required to reproduce typical slopes of γ-ray spectra observed by Fermi/LAT (Ackermann et al. 2011). The break energy $\gamma_b$ is calculated using Eqs. (3), (5), and (6).

Detailed parameters used in our modeling are summarized in Tab. 1.

| Parameter                           | Value                  |
|-------------------------------------|------------------------|
| Black hole mass $M_{BH}$            | $10^9 M_\odot$         |
| Accretion rate $\dot{M}$            | $3 \dot{L}_{\text{Edd}}/c^2$ |
| Accretion disk radiative efficiency $\eta_d$ | 0.1                   |
| Jet production efficiency $\eta_j$  | 1.0                    |
| Energy dissipation efficiency $\eta_{\text{diss}}$ | 0.3                   |
| Jet Lorentz factor $\Gamma$         | 15                     |
| Fraction of energy transferred to electrons $\eta_e$ | 0.5                   |
| Jet magnetization $\sigma$          | 0.01, 0.1, 1.0         |
| Pair content $n_e/n_p$              | 1.0                    |
| Electron injection function indices $p_1, p_2$ | $-1.0, 2.5$         |
| Min. and max. injection energies $\gamma_{\text{min}}, \gamma_{\text{max}}$ | $1, 4 \times 10^4$         |
| Jet opening angle $\theta_j$        | $1/\Gamma$            |
| Observing angle $\theta_{\text{obs}}$ | $1/\Gamma$            |
| BLR photons energy                  | $10$ eV               |
| HDR photons energy                  | $0.06 - 0.6$ eV        |
| BLR radius                          | $0.1 r_{\text{sub}}$  |
| HDR radius                          | $1.0 r_{\text{sub}}$  |
| BLR covering factor $\xi_{\text{BLR}}$ | 0.1                   |
| HDR covering factor $\xi_{\text{HDR}}$ | 0.3                   |

Table 1: Parameters used in numerical simulations.

It should be emphasized here that contrary to the most studies of blazar spectra we use the magnetization parameter, $\sigma$, as an input parameter, instead of magnetic field intensity $B'$ or its energy density $u_B' = B'^2/(8\pi)$. With our input parameters the value of $u_B'$ is determined by the following relation

$$u_B' = \frac{L_B}{\kappa \pi r^2 (\theta_j \Gamma)^2 c} = \frac{\sigma}{1 + \sigma} \frac{1 - \eta_{\text{diss}}}{}^{(1 - \eta_{\text{diss}}) L_{j,0}}{\kappa \pi r^2 (\theta_j \Gamma)^2 c},$$

where $L_{j,0} = 0.5 \eta_j \dot{m} \dot{L}_{\text{Edd}}$ (the value of $\kappa$ depends on the ratio of chaotic to toroidal magnetic component intensity and is enclosed between $4/3$ and $2$).
4. Results

4.1. Energy densities of external radiation fields

If spherically isotropized at a distance $r$ the entire disk radiation would have (in a jet co-moving frame) energy density $\sim L_d \Gamma^2/(4\pi r^2 c)$. Hence, this value sets an upper limit for any contribution to $u'_\text{ext}$ from a disk radiation and its fractions $\xi_\text{ext}$ reprocessed in the BLR and HDR. We visualize these contributions in Fig. 1 as a function of a distance using a parameter

$$\zeta = \frac{4\pi r^2 c u'_\text{ext}}{L_d \Gamma^2}.$$  \hspace{1cm} (13)

For BLR and HDR $\zeta = g_u \xi_\text{ext}$, where $g_u$ accounts for geometry of a source and was introduced and preliminarily studied by Sikora et al. (2013) and Nalewajko et al. (2014b). Figure 1 presents $\zeta$ parameter for spherical and planar geometries of BLR and HDR and geometrically thin accretion disk.

Close to the black hole, at $r < 0.01$ pc, contribution to $\zeta$ is dominated by the accretion disk and was considered by Dermer & Schlickeiser (1993) to be the dominant source of seed photons for the ERC process. However, the absence of a bulk Compton feature in the X-ray band indicates that jets at such distances are not yet enough accelerated and, therefore, radiation produced at such distances is not enough Doppler boosted to explain very large luminosities of FSRQs (Sikora et al. 2005; Celotti et al. 2007). Furthermore, $\gamma$-rays produced too close to the BH would be absorbed by X-rays from the accretion disk corona (see Ghisellini 2012, and refs. therein).

At larger distances accretion disc contribution to $u'_\text{ext}$ drops quickly and BLR starts to dominate. For the spherical model of BLR its contribution is comparable to that of the accretion disk already at 0.01 pc, while for the planar model that distance is about 3 times larger. Maximal BLR contribution to $\zeta$ in both cases is at $r_{\text{BLR}} \sim 0.1$ pc which corresponds with a distance of maximal bolometric BLR luminosity in calculated spectra. At $r > 0.3$ pc contribution to $\zeta$ starts to be dominated by HDR and reaches maximum around 1 pc, just beyond $r_{\text{sub}}$. Then the value of $\zeta$ drops steeply, for the spherical model due to the assumed gradient of the dust radiation luminosity, for the planar model due to assumed presence of outer edge of HDR (see Appendix A).

It is interesting to note that due to stratification of BLR and HDR the value of $\zeta_{\text{BLR}} + \zeta_{\text{HDR}}$ within a distance range 0.03 pc - 3 pc does not vary strongly with a distance, oscillating around 0.1 for spherical geometry and around 0.01 for planar geometry.
4.2. Bolometric apparent luminosities

We calculated apparent bolometric luminosities $L_{bol} = \int L_{\nu} d\nu$ for each radiation process separately and their sum i.e. the total radiative power. Figure 4 presents their dependence on the distance from the central black hole $r$ for three different magnetization parameters and two extreme geometries. Studying bolometric luminosities is a useful tool to investigate radiative efficiency and the dominant radiative mechanism where dissipated energy is deposited. For our models the total value of dissipated energy channeled to relativistic electrons is $L_{el} \approx 6 \times 10^{48}$ erg s$^{-1}$. If total cooling rate is high enough to effectively cool electrons down to energies $\gamma < \gamma_b$, total radiative efficiency is very high, of the order of $70 - 90\%$. It means that the total radiation power is of the order of $10^{48}$ erg s$^{-1}$ as typically observed in FSRQs with $M_{BH} = 10^9 M_\odot$. Such a high radiative efficiency is achievable up to distances $\sim 3$ pc for spherical models and $\sim 1$ pc for planar models. At larger distances $\gamma_{cool} > \gamma_b$ (where $\gamma_{cool}$ is the electron energy at which time scale of radiative energy losses equals the time scale of adiabatic energy losses) and radiation production efficiency drops quickly. Noting that at such distances $\zeta_{HDR}$ decreases faster than $\zeta_{syn}$, dominance of HDR luminosities drops even faster.

4.3. Spectral peaks

Location of luminosity peaks of synchrotron and ERC spectral components in $\nu L_{\nu}$ representation is presented in Fig. 2. The synchrotron peak is located at $\nu_{peak}^{syn} = 3.7 \times 10^6 \hat{\gamma}^2 B^2 \Gamma$, where $B' = \sqrt{8 \pi u_B'}$, and $u_B'$ is given by Eq. (12); the ERC peak is at $\nu_{peak}^{ERC} = (16/9) \hat{\gamma}^2 \Gamma^2 \nu_{ext}$, where

$$\hat{\gamma} = \begin{cases} \gamma_b & \text{for } \gamma_{cool} < \gamma_b \quad (\text{i.e. the fast-cooling regime}) \\ \gamma_{cool} & \text{for } \gamma_{cool} > \gamma_b \quad (\text{i.e. the slow-cooling regime}) \end{cases},$$

(14)

where $\gamma_b$ is given by Eqs. (3), (5), and (6). As long as electrons with energies $\gamma_b$ cool efficiently, the synchrotron peak location drops with distance like magnetic field strength i.e. $r^{-1}$, from $10^{14} - 10^{15}$ Hz at $10^{16}$ cm to $10^{12} - 10^{13}$ Hz at $\sim 1$ pc. At larger distances the synchrotron peaks are produced by electrons with energies $\gamma_{cool}$ and, therefore, their location shifts very fast to higher frequencies, until $\gamma_{cool} = \gamma_{max}$ at $r \sim 10$ pc.

Location of ERC luminosity peaks depends on a dominant source of seed photons at particular distance $r$ and their characteristic energy, $h\nu_{ext}$. Largest values are observed at distances of ERC(BLR) domination and $\gamma$-ray peaks result from Compton up-scattering of photons with energies $\sim 10$ eV of most luminous spectral lines. At $r < 0.03$ pc for planar BLR geometry we can see the effect of the ERC(disk) domination. Much lower – but increasing with decreasing distance – ERC peak location is determined by temperature of
these portions of accretion disk which contribute the most to $u'_{\text{ext}}$ at a given distance along a jet. At distances between 0.3 and 3 pc the $\gamma$-ray luminosity peak is set by ERC(HDR), with energies of the seed photons $h\nu_{\text{ext}} \sim 0.3$ eV. At $r > 3$ pc we see the same effect as in the case of the synchrotron peak i.e. the luminosity peak is produced by electrons with energies $\gamma_{\text{cool}}$ and therefore its location increases with distance very fast up to the distance where $\gamma_{\text{cool}} = \gamma_{\text{max}}$ and then sharply drops. For all models taken into consideration $10^{20} \text{ Hz} < \nu_{\text{ERC}}^{\text{peak}} < 10^{23} \text{ Hz}$.

### 4.4. Compton dominance

Compton dominance parameter $q$ is defined as the ratio of the ERC-to-synchrotron peak luminosities, $(\nu L_\nu)_{\text{ERC}}^{\text{peak}}/(\nu L_\nu)_{\text{syn}}^{\text{peak}}$. Its dependence on a distance from the BH for different parameters $\sigma$ and different external radiation source geometries is shown in Fig. 3. One can easily notice that the shape of $q(r)$ is very similar to the shape of $\zeta(r)$ (see Fig. 1). This can be explained by using approximate scalings of peak luminosities $(\nu L_\nu)_{\text{ERC}}^{\text{peak}} \propto u'_{\text{ext}}$ and $(\nu L_\nu)_{\text{syn}}^{\text{peak}} \propto u'_{B}$. Using Eqs. (12) and (13) one can approximate $q$ by formula

$$q \sim \frac{u'_{\text{ext}}}{u'_{B}} = \frac{(1 + \sigma)\Gamma^2(\theta_j \Gamma)^2 \zeta \eta_d}{4\sigma \eta_j}.$$  

Hence, for the fixed values of $\Gamma$, $\theta_j$, $\eta_d$, and $\eta_d$ the approximate dependence of $q$ on a distance is the same as of $\zeta$, while its normalization depends on $\sigma$. We can see in Fig. 3 that for planar geometries values of $q > 4$, typical for FSRQs, are achievable only for $\sigma < 0.03$. In case of spherical models and $r > 0.01$ pc large values of Compton dominance require $\sigma < 0.3$. All the discussed spectral features for a whole range of studied distances and parameters are presented in Fig. 5 where examples of computed broad-band spectra are presented.

### 5. Discussion

The most diverse opinions about the nature of AGN relativistic jets concern their magnetization, $\sigma$. Being initially dominated by the Poynting flux, relativistic jets are thought to be converted at some distance to the matter dominated flows (see Sikora et al. 2005, and refs. therein). Conversion process can initially proceed pretty efficiently even if the jet is stable and in steady-state (Komissarov et al. 2009; Tchekhovskoy et al. 2009; Lyubarsky 2010a). However, after $\sigma$ drops to unity conversion process becomes inefficient and magnetization decreases much slower with the distance unless being supported by such processes as MHD instabilities, randomization of magnetic fields (Heinz & Begelman 2000), reconnection of magnetic fields (Drenkhahn & Spruit 2002; Lyubarsky 2010b), and/or impulsive modulation of jet production (Lyutikov & Lister 2010; Granot et al. 2011). Little is known about
feasibility and efficiency of these processes in context of AGN and the only chance to verify evolution of magnetization in relativistic jets is by investigating their observational properties over different spatial scales. Close to the jet base such studies can only be performed by analyzing the broad-band spectra in blazars.

Results obtained using the ERC models for $\gamma$-ray production in FSRQs indicate that jets in the blazar zones of these objects are dominated by an energy flux of cold protons (see Ghisellini et al. 2010; Ghisellini et al. 2014, and refs. therein). These results have been obtained by recovering the jet parameters and the location of the blazar-zone from the fits of the observed spectra. However, noticing very poor coverage of the blazar spectra in the far IR and in the 10 keV - 100 MeV band where the synchrotron and ERC luminosity peaks in FSRQs are usually located, a quality of such fits is very limited.

In this paper we present results of modeling of blazar spectra with parameters typical for radio-loud quasars (see Table 1) and assuming suggested by PIC simulations strong coupling between electrons and protons heated in shocks (Sironi & Spitkovsky 2011). The blazar spectra were computed as a function of a distance for three different values of $\sigma$, 1, 0.1 and 0.01 and two geometries of BLR and HDR, spherical and planar, taking into account their radial stratification. As a source of seed photons for the ERC process we also included an accretion disk.

Computed models allowed us to calculate constraints on the jet magnetization as imposed by the spectral features produced at distances within the range $10^{16} - 10^{20}$ cm. Typical for FSRQs values of Compton dominance, $4 < q < 30$, are found to be reproducible for $\sigma \sim 0.1(\theta_j \Gamma)^2$ in case of the spherical geometries of BLR and HDR and for $\sigma \sim 0.01(\theta_j \Gamma)^2$ in case of the planar geometries (see Fig. 3 and Eq. 15). Noting that the real geometries of BLR and HDR are intermediate between the spherical and planar, one may conclude that typical values of the Compton dominance imply $\sigma \sim 0.03(\theta_j \Gamma)^2$. This result indicates that the conversion of the initially Poynting flux dominated jet to the matter dominated jet takes place in the region located closer to the BH than the blazar zone.

Our studies also provide interesting constraints on other model parameters. This particularly concerns maximal and minimal distances of the blazar zone location and pair contents. Due to the fast drop of radiation efficiency at large distances blazar zone should not be located farther than $\sim 3$ pc (see §4.2 and Figs. 4 and 5); due to an increase of the synchrotron peak frequency with decreasing distance the typical observed value $\nu_{\text{syn,peak}} \sim 10^{13}$ Hz (see Ackermann et al. 2011, Fig. 6) is achievable at $r > 10^{17}$ cm, unless $n_e/n_p \gg 1$ (see the left panel in the Fig. 2 and Eq. 6). Contrary, in the ERC(HDR) dominance region, the pair content is required to be negligible in order to keep location of the ERC spectral peaks within the observationally acceptable range (see the right panel in the Fig. 2 and Giommi...
et al. 2012, Fig. 18).

6. Conclusions

Our main results can be stressed as follows:

- large $\nu^\text{peak}_\text{syn}$ at distances $r < 0.03$ pc (§3.3 and Fig. 2) and low radiative efficiencies at $r > 3$ pc (§3.2 and Fig. 4) seem to favour location of the blazar zone in FSRQs within a distance range $0.03 - 3$ pc; this range is similar to the one obtained by Nalewajko et al. (2014a) by using variability and compactness constraints;

- typical values of FSRQ Compton dominance parameter, $q \sim 10$, can be recovered within a distance range $0.03 - 3$ pc for $\sigma \sim 0.1(\theta_j^2 \Gamma^2$ in case of spherical BLR and HDR and $\sigma \sim 0.01(\theta_j^2 \Gamma^2$ for their planar geometries (see Fig. 3 and Eq. 15);

- due to the value of $\gamma_b$ being fixed by the fixed dissipation efficiency $\eta_{\text{diss}}$ (see §2.2) and $\nu_{\text{BLR}}/\nu_{\text{HDR}} \sim 30$, the spectral peak of ERC(HDR) is located at $\sim 30$ times lower energy than the spectral peak of ERC(BLR) (see §4.3 and Fig. 2); noting that $\nu_{\text{peak}}^{\text{HDR}} \sim (n_p/n_e)^2$ MeV, the ERC(HDR) models with significant pair content are rather excluded;

- noting that real geometries of BLR and HDR are suggested by observations to be significantly flattened (see §2), one may conclude that typical values of the Compton dominance imply $\sigma \ll 1$, and therefore, that the conversion of initially Poynting flux dominated jet to the matter dominated jet takes place in the region located closer to the BH than the blazar zone.

Obtained constraints on the jet magnetization can be at least quantitatively relaxed, if noting the possibility that jets in blazars are magnetically very inhomogeneous and that most of blazar emission takes place in weaker magnetized sites being associated with reconnection layers and/or the jet spine region. Such a possibility was investigated by Nalewajko et al. (2014b) following claims that value of $\sigma$ in radio cores is of the order of unity (Zamaninasab et al. 2014), however found by Zdziarski et al. (2014) to be overestimated.

We acknowledge financial support by the Polish NCN grants DEC-2100/01/B/ST9/04845 and DEC-2012/07/N/ST9/04242, the NSF grant AST-0907872, the NASA ATP grant NNX09AG02G.
REFERENCES

Abdo, A. A., Ackermann, M., Agudo, I., et al. 2010, ApJ, 716, 30

Ackermann, M., et al. (Fermi/LAT Collaboration) 2011, ApJ, 743, 171

Celotti, A., Ghisellini, G., & Fabian, A. C. 2007, MNRAS, 375, 417

Decarli, R., Labita, M., Treves, A., & Falomo, R. 2008, MNRAS, 387, 1237

Decarli, R., Dotti, M., & Treves, A. 2011, MNRAS, 413, 39

Dermer, C. D., & Schlickeiser, R. 1993, ApJ, 416, 458

Drenkhahn, G., & Spruit, H. C. 2002, A&A, 391, 1141

Elvis, M., et al. 1994, ApJS, 95, 1

Fuhrmann, L., Larsson, S., Chiang, J., et al. 2014, MNRAS, 441, 1899

Ghisellini, G., & Tavecchio, F. 2009, MNRAS, 397, 985

Ghisellini, G., Tavecchio, F., Foschini, L., et al. 2010, MNRAS, 402, 497

Ghisellini, G. 2012, MNRAS, 424, L26

Ghisellini, G., Tavecchio, F., Maraschi, L., et al. 2014, arXiv:1411.5368

Giommi, P., Polenta, G., Lähteenmäki, A., et al. 2012, A&A, 541, AA160

Granot, J., Komissarov, S. S., & Spitkovsky, A. 2011, MNRAS, 411, 1323

Heinz, S., & Begelman, M. C. 2000, ApJ, 535, 104

Hovatta, T., Valtaoja, E., Tornikoski, M., & Lähteenmäki, A. 2009, A&A, 494, 527

Komissarov, S. S., Vlahakis, N., Königl, A., & Barkov, M. V. 2009, MNRAS, 394, 1182

León-Tavares, J., Valtaoja, E., Tornikoski, M., Lähteenmäki, A., & Nieppola, E. 2011, A&A, 532, AA146

Lyubarsky, Y. E. 2010a, MNRAS, 402, 353

Lyubarsky, Y. 2010b, ApJ, 725, L234

Lyutikov, M., & Lister, M. 2010, ApJ, 722, 197
Marscher, A. P., & Jorstad, S. G. 2010, arXiv:1005.5551
McKinney, J. C., Tchekhovskoy, A., & Blandford, R. D. 2012, MNRAS, 423, 3083
Moderski, R., Sikora, M., & Błażejowski, M. 2003, A&A, 406, 855
Moderski, R., Sikora, M., Coppi, P. S., & Aharonian, F. 2005, MNRAS, 363, 954
Nalewajko, K., Begelman, M. C., & Sikora, M. 2014a, ApJ, 789, 161
Nalewajko, K., Sikora, M., & Begelman, M. C. 2014b, ApJ, 796, LL5
Roseboom, I. G., Lawrence, A., Elvis, M., et al. 2013, MNRAS, 429, 1494
Sikora, M., Begelman, M. C., Madejski, G. M., & Lasota, J.-P. 2005, ApJ, 625, 72
Sikora, M., Stawarz, L., Moderski, R., Nalewajko, K., & Madejski, G. M. 2009, ApJ, 704, 38
Sikora, M., & Begelman, M. C. 2013, ApJ, 764, LL24
Sikora, M., Janiak, M., Nalewajko, K., Madejski, G. M., & Moderski, R. 2013, ApJ, 779, 68
Sironi, L., & Spitkovsky, A. 2011, ApJ, 726, 75
Stern, B. E., & Poutanen, J. 2011, MNRAS, 417, L11
Tchekhovskoy, A., McKinney, J. C., & Narayan, R. 2009, ApJ, 699, 1789
Vestergaard, M., Wilkes, B. J., & Barthel, P. D. 2000, ApJ, 538, L103
von Montigny, C., Bertsch, D. L., Chiang, J., et al., 1995, ApJ, 440, 525
Wilkes, B. J., Kuraszkiewicz, J., Haas, M., et al. 2013, ApJ, 773, 15
Zamaninasab, M., Clausen-Brown, E., Savolainen, T., & Tchekhovskoy, A. 2014, Nature, 510, 126
Zdziarski, A. A., Sikora, M., Pjanka, P., & Tchekhovskoy, A. 2014, arXiv:1410.7310

This preprint was prepared with the AAS \LaTeX{} macros v5.2.
A. Radiation energy densities of external sources

Spherical geometry of external sources

In case of spherical geometry we assume approximate stratification of BLR emission by two functions, $\partial L_{\text{BLR}}/\partial \ln r \propto r$ for $r < r_{\text{BLR}}$, and $\partial L_{\text{BLR}}/\partial \ln r \propto 1/r$ for $r > r_{\text{BLR}}$, where $r_{\text{BLR}}$ is the distance at which maximum of BLR luminosity is produced. For such a stratification energy density of BLR radiation field on the jet axis in the jet co-moving frame is

$$u'_{\text{BLR}} = \frac{\xi_{\text{BLR}} L_d}{6 \pi c r_{\text{BLR}}^2} \times \left\{ \begin{array}{ll} \left( \frac{r}{r_{\text{BLR}}} \right)^{-1} & \text{for } r \leq r_{\text{BLR}} \\ \left( \frac{r}{r_{\text{BLR}}} \right)^{-3} & \text{for } r > r_{\text{BLR}} \end{array} \right., \quad (A1)$$

where $\xi_{\text{BLR}} \equiv L_{\text{BLR}}/L_d$.

For HDR we assume that $\partial L_{\text{HDR}}/\partial \ln r = 0$ for $r < r_{\text{sub}}$ and $\partial L_{\text{HDR}}/\partial \ln r \propto 1/r$ for $r > r_{\text{sub}}$. The jet co-moving energy density of such radiation field is

$$u'_{\text{HDR}} = \frac{\xi_{\text{HDR}} L_d}{3 \pi c r_{\text{sub}}^2} \times \left\{ \begin{array}{ll} 1 & \text{for } r \leq r_{\text{sub}} \\ \left( \frac{r}{r_{\text{sub}}} \right)^{-3} & \text{for } r > r_{\text{sub}} \end{array} \right., \quad (A2)$$

where $\xi_{\text{HDR}} \equiv L_{\text{HDR}}/L_d$ and

$$r_{\text{sub}} = 1.6 \times 10^{-5} L_d^{1/2} \quad (A3)$$

is the graphite sublimation radius (Sikora et al. 2013).

Planar geometry of external sources

Energy density of radiation field on the jet axis in the jet co-moving frame is

$$u'_{\text{ext}} = \frac{1}{c} \int I'_{\text{ext}}' d\Omega'_{\text{ext}} = \frac{1}{c} \int \frac{I_{\text{ext}}}{D^2_{\text{ext}}} d\Omega_{\text{ext}} = \frac{\Gamma^2}{4\pi c} \int_{R_1}^{R_2} \frac{(1 - \beta \cos \theta_{\text{ext}})^2 f_{d}(\theta_{\text{ext}}) \partial L_{\text{ext}}}{r^2 + R^2} \frac{\partial L_{\text{ext}}}{\partial R} dR, \quad (A4)$$

where

$$D_{\text{ext}} \equiv \nu_{\text{ext}}/u'_{\text{ext}} = \left[ \Gamma (1 - \beta \cos \theta_{\text{ext}}) \right]^{-1}, \quad (A5)$$

$$d\theta_{\text{ext}} = \frac{\cos \theta_{\text{ext}} dR}{\sqrt{r^2 + R^2}} = \frac{rdR}{r^2 + R^2}, \quad (A6)$$

$$d\Omega_{\text{ext}} = \sin \theta_{\text{ext}} d\theta_{\text{ext}} d\phi_{\text{ext}} = \frac{R dR d\phi_{\text{ext}}}{(r^2 + R^2)^{3/2}}. \quad (A7)$$

For the optically thick sources (the case of the accretion disk) $f_{d}(\theta_{\text{ext}}) = 2 \cos \theta_{\text{ext}}$, for optically thin sources (assumed to be the case of BLR and HDR) $f_{d} = 1$. Accretion disk is
assumed to extend from \( R_1 = R_g \) (where \( R_g \) is the gravitational radius) to \( R_2 = r_{\text{sub}} \), BLR – from \( R_1 = 0.1r_{\text{sub}} \) to \( R_2 = r_{\text{sub}} \), and HDR – from \( R_1 = r_{\text{sub}} \) to \( R_2 = 10r_{\text{sub}} \) (Sikora et al. 2013).

**B. ERC luminosities**

*Spherical geometry of external sources*

ERC luminosity for spherical external radiation field is (see Eq. 15 in Moderski et al. 2005)

\[
\nu' \frac{\partial L'_{\nu'}}{\partial \Omega'} = \frac{3c\sigma_T}{16\pi} u'_{\text{ext}} \left( \frac{\nu'}{\nu_{\text{ext}}} \right)^2 \int \frac{N_\gamma}{\gamma^2} f_{\text{sc}} \, d\gamma,
\]

where \( u'_{\text{ext}} \) for BLR and HDR are given in our Appendix A, while function \( f_{\text{sc}} \) is specified by Eq. (A3) in Moderski et al. (2005).

*Planar geometry of external sources*

The ERC luminosity produced at a distance \( r \) by Comptonization of radiation reaching a jet from different directions is

\[
\nu' \frac{\partial L'_{\nu'}}{\partial \Omega'} = \frac{3c\sigma_T}{16\pi} \nu^2 \int_0^{2\pi} \int_0^{\pi} \frac{I_{\text{ext}}}{\nu_{\text{ext}}^2} \left[ \int \frac{N_\gamma}{\gamma^2} f_{\text{sc}} \, d\gamma \right] \, d\nu_{\text{ext}} \, d\Omega_{\text{ext}},
\]

where \( d\Omega_{\text{ext}} = d\cos\theta_{\text{ext}} d\phi_{\text{ext}} \), \( \theta_{\text{ext}} \) and \( \phi_{\text{ext}} \) are polar and azimuthal angles of the rays approaching a jet at a given distance \( r \) determined in the external (BH) frame. This equation comes from generalization of the Eq. (15) in Moderski et al. (2005) to include external radiation coming in a jet co-moving frame from all directions and using the Lorentz invariant \( I_{\text{ext}} \, d\nu_{\text{ext}} \, d\Omega_{\text{ext}} / \nu_{\text{ext}}^2 \). For the planar external sources with \( dR \)-rings approximated to radiate mono-energetically but with \( \nu_{\text{ext}} \) being in general dependent on \( R \) above expression for the ERC luminosities takes the form

\[
\nu' \frac{\partial L'_{\nu'}}{\partial \Omega'} = \frac{3c\sigma_T}{8} \nu^2 \int_{R_1}^{R_2} \frac{I_{\text{ext}}}{(\nu_{\text{ext}})^2} \frac{rR}{(r^2 + R^2)^{3/2}} \left[ \int_{\gamma_m}^{\gamma_{\text{max}}} \frac{N_\gamma}{\gamma^2} f_{\text{sc}} \, d\gamma \right] \, dR,
\]

where

\[
I_{\text{ext}} = \frac{f_d(\theta_{\text{ext}})}{8\pi^2 R \cos \theta_{\text{ext}}} \frac{\partial L_{\text{ext}}}{\partial R},
\]

and luminosities \( \partial L_{\text{ext}} / \partial R \) are specified by Sikora et al. (2013) in Appendix A.2.
Fig. 1.— Values of $\zeta$ for spherical and flat geometries of BLR and HDR and flat accretion disk. Black dotted line is a total $\zeta$ for spherical case and black solid line presents a total $\zeta$ for planar geometry.
Fig. 2.— Location of spectral peaks calculated for synchrotron (left panel) and ERC components (right panel) for different values of $\sigma$ and for both planar and spherical geometries of BLR and HDR and flat accretion disk.

Fig. 3.— Compton dominance parameter $q$ for different external source geometries and values of $\sigma$. 
Fig. 4.— Apparent bolometric luminosities calculated for spherical (left column) and flat (right column) geometry of BLR and HDR and flat accretion disk for $\sigma = 0.01$ (1st row), $\sigma = 0.1$ (2nd row) and $\sigma = 0.01$ (3rd row). Black solid line corresponds to total radiative power and black dotted line shows total dissipated power transferred to electrons.
Fig. 5.— Spectral energy distributions calculated for spherical (left column) and flat (right column) geometry of BLR and HDR and flat accretion disk for $\sigma = 0.01$ (1st row), $\sigma = 0.1$ (2nd row) and $\sigma = 0.01$ (3rd row). Solid lines corresponds to sum of all radiation components and grey dotted line shows radio-loud quasar radiation template (Elvis et al. 1994).